IRRIGATION

IRRIGATION:

ITS PRINCIPLES AND PRACTICE AS A BRANCH OF ENGINEERING

BY

SIR HANBURY BROWN, K.C.M.G.

Member of the Institution of Civil Engineers
(late Royal Engineers)

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PREFACE.

IRRIGATION is a subject which covers much ground, and cannot be confined within the narrow boundaries of a single volume. But the principles on which Irrigation Engineering is based can be collected in small compass, and be illustrated by examples of actual practice to the extent that space allows. What, therefore, this work attempts to do is to set forth the guiding principles that should govern the practice of irrigation, and to furnish illustrations of their application in existing canal systems. The majority of the illustrations have been selected from the wealth of material that the irrigation experience of India and Egypt supplies, for the following reasons. In the first place, I have been personally connected with irrigation in both countries, and can therefore handle the facts, relating to them, as one having authority on the subject, and "not as the scribes," whose methods I might be imitating were I to draw my illustrations from the records of other countries. In the second place, it is India that furnishes examples of irrigation on the largest scale, and that has been the school in which all British irrigation engineers, previously to England's occupation of Egypt, have undergone their training. Moreover, the excellent standard work on the subject, "The Irrigation Works of India," by R. B. Buckley, C.S.I., provides in a convenient form more than enough material for copious illustrations, and I have made much use of it, with Mr. Buckley's kind permission. But it will be found that Egypt has been the favourite source of my borrowing. There are two good (so it appears to me) reasons for this. The first is that I am intimately acquainted with Egypt as an irrigating country. The second is that Egypt is *par excellence* the country of irrigation, as it is *wholly* dependent for its existence on its mother, the Nile, from which it has never been weaned.

Engineers entrusted with the execution of important works, such as, for instance, high reservoir dams, would naturally not be content with what they might find on the subject in a book treating of irrigation generally, but would apply themselves to a study of some work dealing exclusively with the special subject of Dams. And so also with other matters which require ample space for adequate description. Concerning such this work attempts no exhaustive treatment, as being beyond the compass of its embrace.

I am much indebted to Mr. R. B. Buckley, C.S.I., for valuable suggestions and much assistance in obtaining and shaping the subject-matter of this book. I am also under obligations to Mr. W. B. Gordon, Director of Irrigation, Cape Colony, and to Mr. W. L. Strange, Director of Irrigation, Transvaal, for sending me information about their charges. The development of irrigation schemes in South Africa is, however, not sufficiently advanced for illustrations to be obtained from the reports sent me. To Mrs. A. T. Kemble my grateful acknowledgments are due for her kind assistance in the compilation of the Index; and to Lady Brown, more than to any beside, for relieving me of all the labour of preparing this work for publication other than that of authorship only.

Among the works consulted in the preparation of this book, the following are perhaps those from which I have borrowed most: "The Irrigation Works of India," by Buckley; "Egyptian Irrigation," by Willcocks; "Manual of Irrigation Engineering," by Wilson; "Irrigation du Midi de l'Espagne," by Aymard; Transactions, American Society of Civil Engineers, International Engineering Congress, 1904, "Irrigation"; Report by Sir William Garstin, G.C.M.G., upon the Basin of the Upper Nile; "Design and Construction of Masonry Dams," by Wegmann; "The Improvement of Rivers," by Thomas and Watt; Proceedings of the Institution of Civil Engineers.

TABLE OF CONTENTS.

CHAPTER VI.

CHAPTER VII.

CHAPTER VIII.

CHAPTER IX.

CHAPTER X.

CHAPTER XI.

CHAPTER XII.

CHAPTER XIII.

NAVIGATION.

PAGE

APPENDIX I.

APPENDIX II.

APPENDIX III.

LIST OF PHOTOGRAPHIC ILLUSTRATIONS.

LIST OF FIGURES.

CHAPTER II.

CHAPTER IV.

CHAPTER V.

CHAPTER VI.

CHAPTER VII.

CHAPTER VIII.

CHAPTER IX.

CHAPTER IX.—*continued.*

CHAPTER XI.

CHAPTER XIII.

IRRIGATION:

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CHAPTER I.

IRRIGATION AND ITS EFFECTS.

IRRIGATION is the artificial process of supplying water to crops in countries where the rainfall is either insufficient or comes at the wrong season for their cultivation. Though agricultural in its object, it has now become a special branch of engineering on account of the nature of the works required for the control of water.

The inequalities in the distribution of rainfall are not only those that relate to time, but also to place. The rainfall of one region may be abundant, of another the reverse. The rainfall of certain seasons of the year may be heavy, while that of other seasons may be light or wanting altogether. In some countries the inequalities of both kinds are not sufficiently pronounced for a distinction to be made between regions of abundant and of scant rainfall, and between rainy and dry seasons. In such countries, if the rainfall exceeds a certain minimum, irrigation is not a necessity; England and the north of France are under such conditions.

In India the variations of rainfall, both as to place and time, are extreme. In Sind and parts of the Punjab the average

rainfall of the year is 3 inches only; in the Central Provinces the annual rainfall is, in places, from 50 to 60 inches; while in the mountains of the west coast and in the Himalayas it varies from 50 to 100 inches and is sometimes as high as 150 inches. The distribution in time is as unequal as the distribution in place. In the Madras Province 12 inches of rainfall, or about one quarter of the total annual amount, is sometimes recorded in twenty-four hours.

So also in the United States of America, the conditions of the country range from arid to humid in consequence of wide variations in the rainfall.

Egypt may be selected as an example of a country under extreme conditions of another sort: it has neither rainy region nor rainy season, and, as far as agriculture is concerned, may be reckoned rainless. But hydrographically it should not be taken alone. Its creation and continued existence is due entirely to the fact that it is a portion of the Nile country, which has its rainy regions in Abyssinia and the Sudan; and that it lies on the track of the run-off of the rainfall. It is this that makes irrigation in Egypt possible. So it is with all irrigation systems—the country irrigated must lie on the track of the run-off of the rain that falls in the catchment area to which it belongs. For rainfall is the primary source of all irrigation, even of that effected from wells.

The scientific land boundary between nations, from an irrigation point of view at any rate, is the water-shed, or line separating catchment areas, whether it be mountain ridges or desert wastes. In the case of the Nile country this principle has been of late years upheld so far as was politically possible, but the possession of the upper reaches of the Blue Nile by Abyssinia stands in the way of any project for utilising Lake Tsana as a storage reservoir for the benefit of the Sudan and Egypt, to which hydrographically it belongs.

The water that is utilised for irrigation must naturally have fallen as rain somewhere in the catchment area above the point

at which it is applied to the land surface. There are some countries which, though their rainfall is so small as to be an absolutely negligible factor in agriculture, have still been renowned for their prosperity, for wealth of crops, and for advanced civilisation in days long past. The best known instances are those of Egypt and Mesopotamia, the lands of the Nile and the Euphrates. Both these rivers in their natural state annually flooded the lands bordering their lower reaches, so that the rain that had fallen in the region where their sources lie was spread over the surface of the country, and a natural system of irrigation by inundation resulted. In Egypt this natural inundation was assisted and controlled by artificial banks and means of regulation with such success that in the time of Joseph "all countries" came into Egypt to buy corn; and, later on, the land of the Nile became the granary of Rome. The artificial system of irrigation which grew out of the natural peculiarities of the Nile is known as the basin system; and is to be found, even to-day, on a vaster scale and in a more elaborately developed stage in Egypt than anywhere else in the world. It was under this system that Egypt attained to the heights of civilisation which it reached under the Pharaohs of the old dynasties.

But the evolution of the Chaldean civilisation seems to have advanced along other lines. For, though it is probable that the newly arrived descendants of Noah found the plain in the land of Shinar dependent for its agriculture on the annually recurring floods of the Tigris and Euphrates, and that they, their predecessors or successors may have introduced some artificial control of the natural inundation, as the Egyptians did, still it is improbable that the later prosperity of Babylonia in the time of Nebuchadnezzar was the result of basin irrigation. In Egypt the flood season is sufficiently early to allow time for the maturing of a winter crop of corn or clover, sown after the subsidence of the flood. In Mesopotamia the flood season is six months later, so that when the waters retire, the parching

summer has begun, when no rain falls to mitigate the scorching heat. Under the extreme conditions of heat and dryness which prevail in summer, it would be lost labour to sow seed which, though it might germinate, would wither away before coming to maturity. So that it would seem that the fertility of the country and the opulence of its cities, as described in Hammurabi's inscription (B.C. 2200), in the Bible, and also by Herodotus, must be ascribed to the introduction and development of a system of perennial irrigation such as we are now pleased to call "modern." The material traces of the canals still exist, and testify to the enterprise and skill of the hydraulic engineers of Chaldea. Hammurabi, one of the greatest monarchs of Babylonia's history, and perhaps a contemporary of Abraham, thus describes in an inscription, older than the Bible record, the effect of irrigation in ancient Chaldea:—

"I have made the canal of Hammurabi, a blessing for the people of Shumir and Accad. I have distributed the waters by branch canals over the desert plains. I have made water flow in the dry channels, and have given an unfailing" (perennial) "supply to the people. . . . I have changed desert plains into well-watered lands. I have given them fertility and plenty, and made them the abode of happiness."

Such results we shall find attend irrigation wherever it is introduced. Fertility and plenty is the sure return. And neglect of the canal works as surely brings ruin. The basis of Babylonia's prosperity and the cause of her decline appear to be indicated in the following passages from the Bible (Jer. li. 13, 42 and 43):—

"O thou that dwellest upon many waters, abundant in treasures."

"The sea is come up upon Babylon: she is covered with the multitude of the waves thereof; her cities are become a desolation, a dry land, and a desert."

It is doing no violence to the text to assert that "the sea" in this connection is the Euphrates in flood. In Cruden's

"Concordance" (1817) under "Sea" is to be found this explanation: "The Arabians, and Orientals in general, sometimes give the name of sea to great rivers, as the Nile, the Euphrates, the Tigris, and others, which by their magnitude, and by the extent of their overflowings, seem as little seas or great lakes. Hence the country of Babylon, which was watered by the Euphrates, is called "the desert of the sea" (Isa. xxi. 1). Jeremiah speaks of it in the same manner (Jer. li. 36): "I will dry up her sea, and make her springs dry." The Egyptians to-day call the Nile the Bahr el Azam, the most excellent sea. Shurippak, the city where Hasisatra, the Noah of the Chaldean Deluge, received his orders to build a ship to save him in the coming flood, was on the banks of the Euphrates. So that the earliest record of any flood was of one in the Euphrates valley.

The latter of the two verses quoted above is remarkable for stating that a flood of waters had for result "dry land and a desert." A passage in the Memoirs of Commander Felix Jones, of the Indian navy, quoted in a lecture delivered by Sir William Willcocks on March 25th, 1903, in Cairo, on the "Re-creation of Chaldea," is in striking agreement with this text, and goes far to explain it. The passage is this:—

"The summit of Opis,[1] as we gaze around, affords a picture of wreck that could scarcely be conceived, if it were not spread at the feet of the beholder. Close to us are the dismembered walls of the great city, and many other mounds of adjacent edifices, spread like islands over the vast plain, which is as bare of vegetation as a snow tract, and smooth and glasslike as a calm sea. This appearance of the country denotes that some sudden and overwhelming mass of water must have prostrated everything in its way, while the Tigris, as it anciently flowed, is seen to have left its channel, and to have taken its present course through the most flourishing portion of the

[1] The ruins of Opis are on the Tigris above Baghdad, at the point where the head works of the ancient canals would have been situate.

district, severing in its mad career the neck of the great Nahrwan artery, and spreading devastation over the whole district around. Towns, villages and canals, men, animals and cultivation, must thus have been engulfed in a moment, but the immediate loss was doubtless small, compared with the misery and gloom that followed. The whole region for a space of 250 miles, averaging about twenty in breadth, was dependent on the conduit for water, and contained a population so dense, if we may judge from the ruins and great works traversing it in its whole extent, that no spot in the globe perhaps could excel it. Of those who were spared to witness the sad effects of the disaster, thousands—perhaps millions—had to fly to the banks of the Tigris for the immediate preservation of life, as the region at once became a desert, where before were animation and prosperity."

Thus Mesopotamia furnishes an example of a country which flourished exceedingly by reason of its irrigation works, and fell to utter ruin when these works were overwhelmed. Some day, in the fulness of time, the successors of the Chaldean engineers will lay firm hands upon the twin rivers and compel them to the service of the lands through which they flow, that the good that has been may be again when the time of regeneration shall come.

A quarter of a century ago Egypt also was suffering from the inefficiency of its engineers and from the decay of its irrigation works; but the latter had not reached the state of ruin, past repair, in which the ancient structures of Mesopotamia are now found. Still, the country was in a bad way and going from bad to worse, when those who were called in to prescribe recognised that, for a country that was wholly agricultural and whose agriculture was entirely dependent on irrigation, the one thing needful was efficiency in its irrigation service. The story of Egypt's recuperation cannot be told here, but the ultimate results which followed the substitution of efficiency for inefficiency in the control of the Nile waters may be

enumerated in general terms as follows:—The cotton crop, the modern source of Egypt's wealth, has increased from 3,000,000 to 6,000,000 cwt., or in value from £7,500,000 to £15,000,000; the maturing of the maize—the peasants' food crop—has been assured by its timely sowing being made a certainty; the cost of raising crops has been lessened by improved means of irrigating them; the cultivable area has been increased from 5,000,000 to 6,000,000 acres; the value of land has been more than doubled; and the system of forced and unpaid labour, with its attendant abuses, has been abolished. The capital expenditure which produced these results was about £4,000,000. This figure does not include the expenditure on the Assuan dam and other works connected with it, the construction of which came after the realisation of the benefits enumerated. The further development of Egypt, to be expected as the result of these later works, is as yet incomplete.

The historical record of irrigation in India does not go so far back as that of Mesopotamia or Egypt. It was about 300 B.C. that Megasthenes, writing of India, referred to the advantage of double crops resulting from irrigation, whereas the cuneiform inscription of Hammurabi, already quoted, furnishes evidence of the practice of irrigation in Babylonia as far back as 2200 B.C.; and the hieroglyphic records of the Pharaohs of the twelfth dynasty, of date about 2500 B.C., do the same for Egypt.

But it is modern results which are of present interest from a practical point of view. As one of the most recent constructions, the Chenab Canal is a noteworthy example. Mr. R. B. Buckley, in "The Irrigation Works of India," thus describes the effect of its construction:—

"The tract which it commands, known as the Rechna Doab, is nearly all Crown land. Before the construction of the canal it was entirely waste, with an extremely small population, which was mostly nomad. Some portion of the country was

wooded with jungle trees, some was covered with small scrub camel thorn, and large tracts were absolutely bare, producing only, on occasions, a brilliant mirage of unbounded sheets of fictitious water. Such was the country into which 400 miles of main canals and 1,200 miles of distributaries now distribute the waters of the Chenab, turning some 2,000,000 acres of wilderness into sheets of luxuriant crops. . . . About 1,500,000 acres of the Crown lands have now been allotted to colonists, and a new population of a million people have founded homesteads which they cultivate with the waters of the Chenab Canal."

Considering India as a whole, the result of the work done by the engineers of the British Government during the past half-century is an increase of the area watered by Government irrigation works from 3,000,000 or 4,000,000 to 21,500,000 acres, brought about by a capital expenditure of about £30,000,000, on which the net profit amounts to 7 per cent. This takes no account of the indirect profits. The value of the crops raised is estimated at £26,000,000, or 87 per cent. of the capital expenditure on the canals by which they are irrigated. But this must not all be written down to the credit of irrigation, as the crops in India, in most cases, are not entirely dependent on canal water, as they are in Egypt, and, except in years of drought, there would not be total failure of the crops, even if the canal supply were entirely cut off. It is generally reckoned in India that irrigation increases the gross outturn by about 30 per cent. The Chenab Canal is an exceptional case in which, perhaps, the whole yield, or almost the whole, may be credited to the canal. Exception also has already been made of years of drought. A canal system serving a tract which is severely affected by a serious deficiency in the rainfall may in a single year save crops equal in value to its entire capital cost.

The result of irrigation in the United States is thus described by Mr. Elwood Mead in his paper read at the International

Engineering Congress of 1904: "Since 1900 the arid region has enjoyed great prosperity. There has been an increase in western settlement, and the values of both land and water have had rapid and continued advance. Land in the Yakima valley, Washington, which could have been purchased five years ago for $15 an acre, now sells for $75 an acre. Land in the Turlock and Modesto districts, in California, which sold for $20 an acre three years ago, now brings $60 an acre. Water rights in Idaho, which in 1894 found no buyers at $10 an acre, now have prompt sale at $25 an acre."

In a work entitled "Irrigation in the United States," by Newell, published in 1902, the following information is given: The arid regions, which include two-fifths of the area of the United States, have an average annual rainfall of 20 inches or less. Of the arid land and semi-arid regions 470,000,000 acres is grazing land; but it appears that the actual amount of land which is irrigable is, as variously estimated, from 60,000,000 to 100,000,000 acres—a field for irrigation of extent sufficient at least to satisfy the present generation. The arid regions extend, moreover, southward into Mexico and northward into Canada, so that in these two countries also there is ample scope for irrigation engineering. Mr. Newell states that twenty to thirty acres of open range in the arid regions is generally considered sufficient for the support of a cow, and that the same land under irrigation will feed ten cows. This agrees with the experience in England, where rain takes the place of irrigation, the association of three acres and a cow being familiar to politicians as well as farmers. Mr. Newell further states that "the open range may have a value of 50 cents an acre, while under irrigation the selling price may rise to $50 per acre, or even $500 per acre when in orchard."

In a paper on "Irrigation in the Transvaal," by M. R. Collins, published during 1906 in Vol. CLXV. of the Proceedings of the Institution of Civil Engineers, it is stated, with reference to the value of land in the Transvaal, that "a liberal

estimate of the value of good unirrigated land would be £3 to £5 per acre. Each acre of land is enhanced in value by £25 by being brought under irrigation."

In Europe the countries that practise irrigation are France, Italy and Spain.

In Northern and Central France irrigation is not a necessity for raising crops, but it is, all the same, taken advantage of to increase the fertility of meadow lands for hay crops. The prosperity of Normandy, for instance, is due to regular irrigation. In Southern France, however, where the summers are very dry and hot, irrigation is useful, if not indispensable, for all kinds of cultivation, particularly meadows. Market gardening is impossible without it. It has been estimated that irrigation in France brings an increase in net earnings of at least 200 francs per hectare (£3 7*s*. 6*d*. per acre). Sir Colin Scott-Moncrieff states, in "Irrigation in Southern Europe," 1868, that "in Vaucluse, in the south of France, the rental of good land not entitled to irrigation is about £3 4*s*., and, if it can procure it, it rises to about £4 3*s*. per acre"; and further adds that irrigation causes an increase of 50 per cent. in the price of land.

Italy is the country of irrigation in its most advanced stage of development. The plains of Piedmont and Lombardy provide material for the liberal education of an irrigation engineer, and show what artificial control of the natural water supplies of a country, in competent hands, is capable of effecting.

Lastly, there is Spain. As Italy owes much of its irrigation laws and customs to the ancient Romans, so is Spain indebted to the Moors. Valencia, Murcia and Granada, Elche and Lorca, had Moors for their first irrigation engineers, whose works remain, active and beneficent, in the hands of the conquerors who expelled the enterprising race that constructed them. The irrigation works of Valencia are supposed to have been executed about A.D. 800. For nearly three hundred years after the final expulsion of the Moors from their last stronghold

of Granada little was done by the Spaniards to extend the area of irrigation. But during the reign of Charles III., A.D. 1785 to 1791, dams were built for the storage of water and a fresh impulse given to irrigation. The dams of Spain vary in height from 21 to 48 metres (69 to 157 feet).

The result of irrigation in Spain on land values is remarkable.[1] From certified copies of sales during the year 1859 the following appears: The average price of irrigated ground at Castellon was £140 per acre, the average price of the ground without irrigation in the same neighbourhood being £10. In Murcia the price of irrigated land was £500 per acre, of ground without irrigation £25 to £30. Near Madrid irrigated land was leased for £5 an acre, while unirrigated land could be bought outright for that figure. As a rule, for the whole of Spain, good land without irrigation in the valleys could be bought at an average price of from £6 to £10, and the same land irrigated at £80 to £120 per acre.

It is thus abundantly evident that, where rainfall is deficient or capricious, but the soil is cultivable, irrigation is a most potent agent for converting land, of little value without it, into valuable property; that a well-administered system of irrigation may double the value of property that has hitherto been served by a badly managed system; and that in a country dependent on irrigation, the neglect to maintain its canal works in a state of efficiency will result in its impoverishment and ultimate ruin.

[1] Proceedings of Inst. C.E., "Irrigation in Spain," by Higgin (1869).

CHAPTER II.

BASIN IRRIGATION.

THE earliest form of irrigation was probably a natural one, brought about by rivers overflowing their banks during seasons of flood. Egypt, on the Nile, and Mesopotamia, on the Tigris and Euphrates, have already been cited as countries in which the genesis of irrigation was probably of such a kind. Sind, on the Indus in India, is another notable instance. Most rivers with periodical flood seasons have their sources in mountain ranges, where the rainfall is heavy and the ground is rocky. In such cases the declivity of a river is, at first, very great, and the velocity of the stream is torrential. The detritus, which is washed down from the steep slopes of the hills and eroded from the bed, is carried forward to the point beyond the foot of the hills where the slope of the stream becomes reduced. Here erosion ceases and deposition of the heavier detritus commences. Fan-shaped layers of deposits spread themselves out, and, in process of time, force the stream to take a new course. Again the depositing process is repeated until the general country level is raised. At length the stream cuts a way through its own deposits down, perhaps, to bed-rock, and flows forward in a deep channel through the softer plains. Gradually the velocity becomes less rapid and the channel less deep as the water flows seawards, until at length the river enters the region where it overflows its banks in flood.

From that point onwards the bed of the river and the lands alongside are being gradually raised by the material brought down by the water, while the delta of the river is being constantly added to along its seaward margin by the deposit of the

annual flood. When the river tops its natural banks and the flood waters leave its channel, the velocity of flow of the escaping water rapidly diminishes, and, in consequence, the silt in suspension is deposited in greatest quantity within a short distance from the river edge; so that, in course of time, the lands assume a downward slope away from the river. This is the explanation of the fact that, in the case of wide flat valleys traversed by rivers with a periodical overflow, the highest land is found along the river edge. If there are several branches traversing a level delta, the surface slope will be away from each until it meets the slope formed under the influence of the adjacent channel. Along the meeting line an escape channel will probably be formed by the flow-off of the flood waters, which takes place when the river falls. The delta of Egypt and the deltas of India furnish examples of this formation, the further development of which has been arrested by the construction of protective banks to guard the irrigated crops from being damaged by flood. The Nile valley of Upper Egypt exhibits this characteristic in its simplest form. The single channel of the river traverses the valley, and its floods spread sideways over the land on either side of it. There is thus formed a land surface of the form shown to an exaggerated scale in Fig. 1. In such a valley as that of the Nile in Upper Egypt the flood waters of an inundation, if uncontrolled by artificial works, would move forwards over the land as a shallow sheet of water with its surface lower than the river level opposite, and only partially submerging the land. In very extreme floods, however, the level of the inundation would be everywhere the same as that of the river alongside. There would be certain lengths of the high margins of the river lower than other parts, and, over these, ordinary floods would find their way to the lower land beyond; but the highest floods would overtop the river margin everywhere. A low flood would probably not find its way to the low land at all, except in small quantity through natural channels formed by the waters of previous high floods

cutting their way back to the river. The first thing that would occur to the inhabitants as a method of securing an inundation, whether the flood were low or high, would be to make cuts through the high land along the river edge, whereby water would be admitted to the more remote lands below flood level. They would then endeavour to make the water rise over the higher lands by placing obstructions in the way of the forward

INUNDATION DIAGRAMS

FIG 1

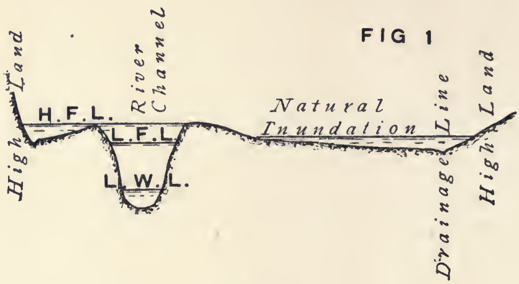
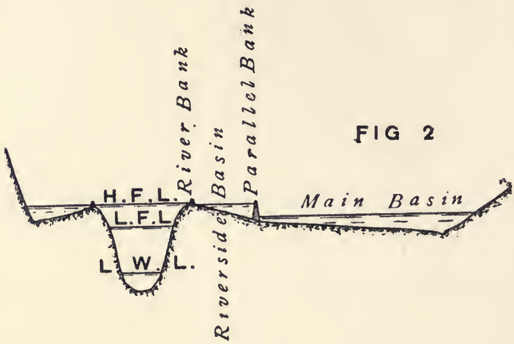


FIG 2



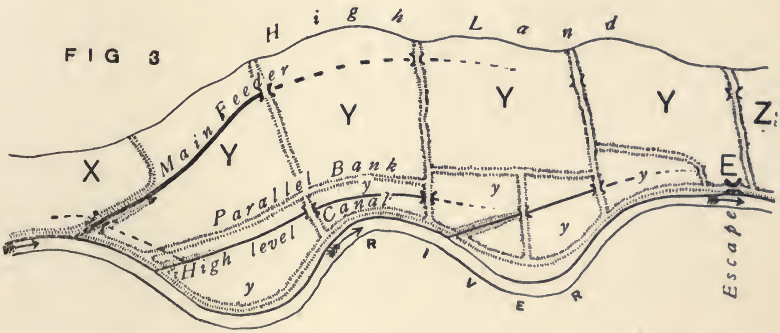
flow of the water thus introduced to the lower lands. By some such process as this, short inundation canals and cross embankments would come into being. Then, to prevent the cross embankments from being swept away by the effects of a high flood, a protective bank along the river edge, to exclude excess, would be felt to be a necessity.

But with such arrangements the inundation of the comparatively high land near the river would have been a constant

difficulty, necessitating inconveniently high cross embankments to hold the water up sufficiently. On this account the advantage of separating this width from the remainder, and of providing for its irrigation by independent canals, would have suggested itself. For this purpose a longitudinal bank would be made along the line where the comparatively steep slope near the river changes to the flatter slope of the more remote land. The strip alongside the river, thus separated from the lower lands, would be given its own canal, in which the water would be held up to the maximum level that the flood in the

IMPERFECT BASIN SYSTEM

FIG 3



river could produce. The result, in a favourable flood, would be as shown in Fig. 2.

In the chain of basins along the lower land arrangements would have to be made to pass on the water from basin to basin. At first this would be done by means of openings (bywashes) at the ends of the banks on the higher ground, protected probably by loose stone. Cuts would be made in the banks, along the line of flow-off in the lowest land, when it was desired to finally get rid of the water. These cuts would later on be replaced by masonry regulators and escapes to give better control. There would thus be created a system of basins arranged as in Fig. 3. This figure will serve to illustrate the defects of the arrangements when the basin system had reached this stage of evolution.

Y, Y, Y are the main basins of a chain; X the terminal basin of the next chain above; *Z* the initial basin of the chain next below the Y chain. The smaller basins *y, y, y* are those which include the high margin of the river. The main basin-feeder discharges into the first basin Y, from which the water is passed on to the other basins in succession. The level in each basin is so regulated by the escapes in the cross embankments that the water may cover the highest land; and thus a succession of water terraces is formed. The escape E at the tail of the chain passes any excess there may be back into the river and provides for the final emptying. The smaller basins *y, y, y* are worked in a similar way.

Now, in arranging for the supply of water to a basin system, there are two important principles to be observed. The first is that, in a year of low flood, the supply should be delivered in such quantity and at such levels that the whole of the land may be submerged during the period of flood to the extent that saturates it sufficiently to secure that the crop, which will be sown after the flood, shall germinate and come to maturity without further irrigation. The second principle is that full advantage should be taken of a good flood to enrich the soil by encouraging the deposit of the fertilising matter which the river brings down in suspension from its sources; and that this deposit should not only be as abundant as possible, but should be evenly distributed over the whole area of the chain of basins.

In the scheme depicted in Fig. 3 these two principles are not observed. The chain of basins Y, Y might perhaps in a low flood get filled by water passed on from X; but the case of the smaller basins *y, y* would be hopeless without a syphon connecting the high-level canal with the upper system X, as shown by the dotted line.

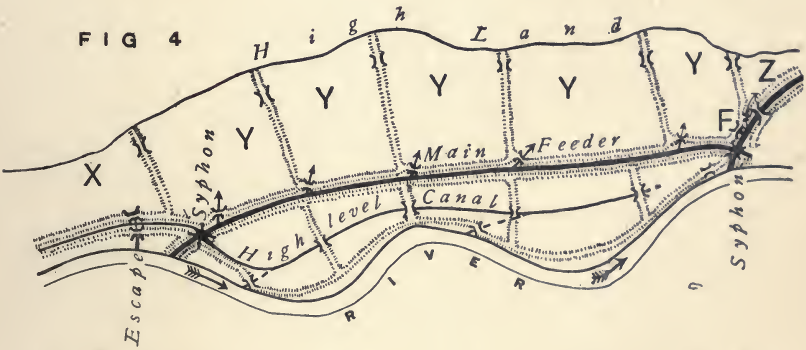
The second principle enunciated, concerning the distribution of muddy flood water, has next to be considered. It is conceivable that the high-level canal will satisfy this principle in a

high flood; in a low flood, without a syphon connection with the upper chain, it will not flow at all. But the main basin-feeder is altogether out of order. It discharges into the first basin from a channel without banks, and creates a shallow lake from which the second basin is fed through the cross embankment. In the same way the third is fed from the second, the fourth from the third, and so on. Consequently the first basin gets most of the muddy deposit and the lowest basin the least.

An arrangement of canals and banks in a basin chain, which pays due regard to the principles laid down, is shown in Fig. 4.

IMPROVED BASIN SYSTEM

FIG 4



The main basin-feeder, instead of discharging into the first basin, passes by it between banks, and is carried, approximately, along the same alignment as the bank of Fig. 3 which separates the high and low basins. At the upper corner of each basin is a feeder-sluice to fill the basin and give it muddy water, so that all may get a fair share of the fertilising matter. The masonry works situated in the banks of the basins, at the points where they cross the natural drainage line, serve to regulate the basin levels and to empty the basins at the proper time; also to connect one chain with the next one above and below, so that water can be passed from one chain to another when it is advantageous to do so.

By means of the syphon canal, high level water, derived from a point on the river at a considerable distance up-stream, is furnished to the lands beyond the basin-feeder, which, without it, would be dry in low flood years. Though this arrangement secures water to the high level tract, the old direct heads from the river should not be suppressed, as in high floods it is of advantage to admit a supply through them on account of the increase of fertilising deposit to be obtained by so doing. All the old direct feeders of short run should be maintained with the object of so using them that full advantage may be taken of high floods when they come.

If a chain of basins can be linked up with the chain next above it, the canals of the upper chain can be so disposed and designed as to effect the inundation of all the lands as far down as the point where the waters of the main feeder of the lower chain comes to country surface. But, if a chain of basins is in the unfortunate position of having no chain above it, there will be land on either side of its main feeder, from its off-take on the river to the point where its water comes to country surface, which cannot be flooded. In high floods the unflooded area may be little or nothing; in low floods it may be considerable.

The selection of the points at which the main feeders take off depends on the windings of the river and the configuration of the land to be irrigated. The position of the off-take on the river has a great influence on the silting tendencies of the canal. The original constructors of the inundation canals of India found that it was best to take off at points screened from the full force of the current, and, therefore, preferred as a site for the head of an inundation canal a point on a side branch of the river some little distance above its lower junction with the main stream. The soundness of this practice is confirmed by the case of a canal in Egypt, the Abu Bagara, which takes off a side branch of the Nile near its lower end, and is the only old inundation canal in Egypt which does not silt. The principles formerly followed by the Arab engineers in Egypt (as stated by

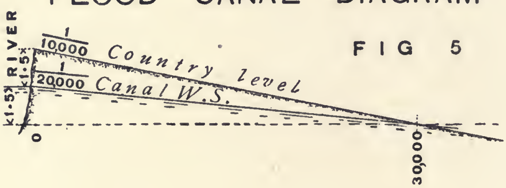
Colonel J. C. Ross in "Notes on the Distribution of Water, and the Maintenance of Works in Upper Egypt. Cairo, 1892") are opposed to the original Indian practice, being as follows: "The off-take should be placed in the bank along which the deep water of the Nile flowed." This rule is stated in a form as if for guidance, but it lays down a misleading principle. If the Arab engineers are correctly credited with the observance of this principle, it does not follow that they are worthy of imitation, for neither theory nor experience lend their support to the soundness of this practice. Theoretically the most favourable place to select for the off-take is any point past which the river flows with the same velocity as the canal will flow after the water is drawn into it, so that there may be no change of velocity. If the canal has its off-take so situated, there should be a minimum of silt deposit in the canal consistently with a maximum of silt carried forward in suspension to the fields. The question of silt deposit will be discussed in a future chapter, when it will be shown that one of the conditions of bringing about a diminution of silt deposit in a canal is an absence of high velocity in the river at the point of off-take.

The site of the off-take having been decided upon, the slope of the land surface determines the water surface slope to be adopted in the feeder canal. Supposing the land on the alignment of the canal to have a slope of $\frac{1}{10000}$, the canal water surface slope might be $\frac{1}{20000}$. The statistics of previous floods must be studied to determine the duration of the flood and its levels. In order that the inundation may not fail in bad years, the project should be based on the levels of a low flood, and on the period during which the canals would flow to effect the filling of the basins; remembering that, even if the river levels admitted of it, the filling cannot be prolonged beyond a certain date, as the basins must be emptied and the land surface be prepared to receive the seed of the coming crop before it is too late for the sowing. In Egypt fifty days is the full period of

filling. The mean flood level of this period is, for example, 1·50 metres (or, say, 5 feet) below the country surface at the point where the canal takes off from the river. If, then, the country slope is $\frac{1}{10000}$, and the canal water surface slope $\frac{1}{20000}$, the water will come to land surface at a point thirty kilometres (19 miles) from the canal head, as shown in Fig. 5. Down to this point, then, the canals of the upper system (if there is one) must be carried, and the land must be considered as belonging to the upper chain for the purpose of calculating the dimensions of canals.

The bed level of the feeder canal should be fixed at that level below the average level of the flow period which will give the

FLOOD CANAL DIAGRAM



discharge required with a channel of a convenient bed width. By the "average level of the flow period" is meant the mean of the levels of the flood at the canal head between the date that water is admitted into the canal to feed the basins and the date when the head is closed to shut off the supply. To determine what the dimensions of the canal should be, a calculation must be made of the quantity of water required to fill the basins depending on the feeder, lying between the point where the water comes to country surface and the point where the water of the canal in the chain next below does the same. The inundation should be of such proportions that the highest ground in any basin would be covered by a depth of at least 30 centimetres (1 foot) of water. The basins of Egypt vary in size from 3,000 to 50,000 acres; the mean depth of the inundation varies from $\frac{3}{4}$ metre ($2\frac{1}{2}$ feet) in small basins to $1\frac{3}{4}$ metres ($4\frac{3}{4}$ feet) in large basins. But, as a rough estimate, sufficiently

correct when we are dealing with principles, 5,000 cubic metres (176,000 cubic feet) may be taken as the quantity required per acre of land to be flooded, inclusive of the quantity required to make good the loss by evaporation and absorption during the period of inundation. The daily discharge of the main feeder for the fifty days' period of flow must, therefore, be $\frac{1}{50}$th of 5,000 cubic metres, or 100 cubic metres, per acre to be flooded. The mean flood level of the fifty days' period, used as one of the data in the designing of the canal, need not be that of an *extreme* low flood such as comes but rarely, as in such years a diminished quantity of water must be made to do increased duty by bringing each basin in succession up to full inundation level with the discharge of the basin next above in order.

The bed level and width of the feeder canal can then be determined with these data, namely, the mean flood level, the daily discharge, and the water surface slope in the canal.

To deal satisfactorily with the large bodies of water that have to be distributed over the extensive areas of a chain of basins perfect control over the water at all points is necessary. This is only to be obtained by a complete system of regulating works, such as head sluices, to draw the water from the river into the feeder canal; basin sluices, to admit water from the canal into the basins; regulators in the basin cross banks to pass on the water and regulate the level in the basins above them; and escapes to discharge the water back into the river.

If the head sluice of the feeder canal is built near the river edge, it may be in danger from river erosion: for this reason it is generally placed at some little distance from it, in spite of the objection that the channel up stream of the head silts up badly when the head is closed. It is sometimes constructed on the top of the syphon which carries the water of the upper chain under the main feeder. Such an arrangement has this to recommend it, that the head sluice can be so designed that its weight may resist the tendency of the syphon to blow up

when it is working under a head; but it has the disadvantage that the design is necessarily complicated, and it is difficult to arrange for the traffic which passes across the canal and along its banks.

Again, the head may be built at such a distance down stream of the syphon as to allow room for a basin escape to be built between the two. The basin chain would then empty itself by the escape into the off-take channel of the feeder canal, by which, if the head sluice openings were closed, the discharged water would find its way into the river. This arrangement is shown at F in Fig. 4.

At the tail end of the chain of basins the main escape may be either situated as just described (F, Fig. 4), or may be placed as at E. This latter arrangement is of the nature of a level-crossing over the canal leading to the syphon. In the left bank of the syphon canal an inlet regulator passes the basin water into the canal, and an escape in the opposite bank discharges it into the river. The syphon down stream of the level-crossing is fitted with regulating apparatus, so that the syphon canal can be wholly or partially closed at will.

The discharging capacity of the main escape has next to be considered. The quantity of water to be finally discharged at the tail of a chain will be the volume contained in the basins, and will be less than the estimated quantity required for the filling by the amount allowed for evaporation and absorption. For rough calculations it has been the custom in Egypt to estimate the quantity to be discharged at the rate of 4,000 cubic metres (141,000 cubic feet) an acre, which allows nearly a metre (or 3 feet) as the mean depth of the inundation. But, as the water must be got rid of in time for the sowing of the saturated ground, a period of only about twenty days can be allowed for the emptying, against fifty days for the filling, and, therefore, the tail escape must be designed to effect the discharge in the shorter period. The discharging power of the escape, which depends on the river levels at the time of discharge, will be greater when the river

is low than when it is high; whence it happens that in good floods, at any rate if they are late in falling, the escapes work slowest when there is most water to be got rid of. The escape should, therefore, be given ample water-way, so that it may prove sufficient under adverse conditions. It should also be given an extended apron and ample protection of well revetted slopes and talus of heavy pitching down stream, as, in the opposite case of a low river, the escape will have to work for a prolonged period under the severe conditions of a considerable head. This same precaution must be taken in the case of the regulators in the cross-embankments of the basins, as they discharge into wide expanses requiring an enormous volume of water to affect the surface level, so that the head remains undiminished. In other respects the design of such works may be the same as that of ordinary regulators; the volume of water to be passed, the time to be allowed for passing it, and the head under which the discharge will be effected determining the water-way to be allowed in each case.

The programme of operations in the filling and emptying of a chain of basins is, in general terms, somewhat as follows:—

On a fixed date (generally August 10th in Upper Egypt) the basin feeder heads are opened, and the basins commence to fill. The escapes are likewise opened so as to admit river water also by them into those basins which are in connection with the escape channels; but, as soon as the water coming from above causes a reverse flow back into the river, the escapes are closed again. The basin-filling by the feeder canal continues at a rate depending on the river levels. At the same time, water is passed forward into the canals overlapping the feeder of the next chain.

One of the principles laid down for observance in the designing and working of a basin system is that full advantage should be taken of a good flood to obtain the maximum deposit of fertilising matter possible; and one way of doing this is to pass as much water as possible through the basins. To effect this, the head sluice of the feeder canal should not be closed

when the basins are full, but should be left open, and the levels in the basins regulated by the opening of their escapes to the necessary extent. In this way a quantity of water is admitted to the basins in excess of that required to fill them, and, as the current in the wide expanse of water is imperceptible, a larger volume of silt is deposited and the land therefore derives greater benefit.

In fifty days after the first admission of water, or less if the flood is a good one, all the basin land should be under water; and a week later (October 5th) the basins should be ready to discharge. The feeder heads are then shut down, and the supply from the river cut off; the upper basins are discharged on to the lower to complete their inundation, if still incomplete, and the water passed forward from basin to basin to the tail of the chain, where it is finally got rid of through the escape into the river. In a fortnight or three weeks the basins should be empty, with the exception of the water in the lowest hollows which drains off more slowly. The seed of the basin crop —wheat, beans or clover—is then scattered broadcast over the surface ooze and merely pressed into it by a plank drawn over the ground; or else, after a short interval of drying, the land is lightly scratched with a plough before the seed is scattered. The crop is then left to take care of itself till it is ripe for harvest.

Before leaving the subject of basin irrigation it may be useful to note the dimensions of the basin banks adopted of late years in Egypt. The principal basin banks, and the river bank, have a crest width of 5 metres (16 feet) and side slopes of 2 of base to 1 of rise. The crest level is made $1\frac{1}{4}$ metres (4 feet) above highest water level. The slopes exposed to wave action on the side of the prevailing wind are, in the completely remodelled banks, protected by dry rubble pitching to heights varying with the intensity of the wave action; or else by a dwarf masonry wall where the action is too severe for dry rubble to resist. In the case of banks exposed to water on one side only, the unexposed slope is made with a base of $1\frac{1}{2}$ to a rise of 1.

The crest width of the less important banks of small height varies between 3 and 4 metres (10 and 13 feet), and the crest level is a few inches lower, with reference to the high water level, than in the case of the more important banks.

In India, the area of cultivation dependent on inundation canals, maintained by Government, is about 4,000,000 acres. There is, in addition, land irrigated by canals belonging to private owners, and by other canals belonging to a native State.

The chief inundation canals of India are to be found in the basin of the Indus and its five tributaries. The almost rainless district of Multan is rendered abundantly fertile by a series of inundation canals fed by the Sutlej and the Chenab on either side of it. Sind, also nearly rainless, raises crops of over 1,500,000 to 2,000,000 acres by means of the irrigation provided by 6,000 miles of inundation canals. In one respect the inundation canals of the Punjab in India differ widely from those of Egypt. The latter have a bed slope of $\frac{1}{20000}$; while the canals of the Punjab have sometimes as steep a gradient as $\frac{1}{4000}$, and rarely less than $\frac{1}{10000}$. This difference is due to the fact that the slope of the country is much steeper in the Punjab than it is in Egypt. Consequently the flood water of the Punjab rivers can be brought to soil surface after a much shorter run in the canal than is possible in Egypt.

There is one other respect in which the inundation system of India differs from that of Egypt. In Sind and the Punjab in India a large proportion of the work done by the inundation canals is in the irrigation of the *kharif* crops—jowar, bajra and rice. These crops are irrigated during the flood season by the inundation canals in the ordinary way, that is, by field channels fed "free-flow" from the canals, as distinguished from a system of inundation. But for the *rabi*, or cold weather crop of wheat (chiefly), the fallow land is inundated by the flood water with the same object as in Egypt, namely, to manure the surface of the ground with a layer of silt deposit, and to saturate it

sufficiently for the needs of the winter crop. In Sind the *rabi* area so inundated bears only a small proportion to the whole area irrigated from the inundation canals; whereas in Egypt almost the whole of the flood irrigation consists of the inundation preparatory to the sowing of the winter crops—wheat, beans and clover. There is a comparatively small area of millet, raised by flow from the flood canals of Egypt, which corresponds to the flood irrigation of *kharif* crops in India. It would, therefore, seem more correct to call such canals in India flood canals, inasmuch as they irrigate in the ordinary way during the flood, and inundate to a less extent; whereas the basin canals of Egypt are true inundation canals, as the ordinary irrigation of millet done by them is insignificant in amount in comparison with that effected by inundation. There is no basin system in India, properly so called, such as there is in Egypt. The inundation canals of India work independently of one another, without connection or overlapping of spheres of influence, so that there is no opportunity afforded for correcting the shortcomings of a low flood by leading water from a higher system into a lower one.

It is interesting to find that the principle of the basin system of Egypt has been adopted by the farmers of the North Western Plateau of Cape Colony in South Africa. Their practice is thus described in a report written by Mr. W. B. Gordon as Director of Irrigation of Cape Colony.

"The most successful works in this tract are undoubtedly those which have been constructed by the farmers themselves, for the utilisation of the intermittent flood waters on the flat lands or 'vleis' adjoining the rivers, more especially the Zak river, along which these vleis are especially numerous. The water is diverted from the river by means of a cheap masonry weir, or, where rock is not available, by means of an earthen dam constructed bank-high across the river and washed away by every moderate flood. Sluit channels, or

'furrows' as they are called, convey the water on to the lands where it is held up to a maximum depth of three to five feet by small banks or 'saai' (*i.e.* sowing) dams constructed across the vlei. When the sowing time arrives, the impounded water is let off to moisten the lands below the dam, and these, together with the saturated lands above, are then ploughed and sown."

CHAPTER III.

PERENNIAL IRRIGATION AND WATER "DUTY."

UNDER the basin system, described in the last chapter, only one crop can be raised during the year, and that only a winter crop of cereals or beans. The more valuable summer crops cannot be grown. These latter require periodical waterings when the river is low, and protection from inundation when the river is high. The system of irrigation under which such crops can be matured is known as "perennial," the water supply being continuous throughout the year. When such a supply is obtainable for irrigation, an average of two crops a year can be grown. The mean value of a perennially irrigated crop is greater than the value of a single basin crop of wheat or beans. Hence it follows that, as two crops a year are raised under the perennial system and only one under the basin system, the value of the crops in the former case is more than double that in the latter, which accounts for the fact that both the selling and renting value of perennially irrigated land is more than double that of basin land. The preference for perennial irrigation, wherever it is possible, is, therefore, quite natural. One of the results of the building of the Assuan dam on the Nile, and of the storage of water above it for use in the summer months, will be the conversion of 450,000 acres of basin land into land under perennial irrigation. This is the most modern instance of the development of perennial irrigation at the expense of the flood system.

The earliest definite record of perennial irrigation has already been given in the first chapter. Hammurabi, who ruled in Babylonia about four thousand years ago, must be accepted as

the oldest known constructor of perennial canals. But, though it has been assumed that Egypt under the Pharaohs owed her prosperity to the basin system of irrigation, and that perennial irrigation was not introduced into Egypt till quite recently, in Mehemet Ali's time, it is by no means improbable that the extreme north of the Delta enjoyed perennial irrigation in Ptolemaic and Roman times, and had enjoyed it possibly for centuries before Hammurabi dug his Grand Canal of Babylon. For, two thousand years ago, there was still in working order a remarkable natural reservoir in connection with the Nile, known as Lake Mœris. According to Herodotus, who visited the lake about 454 B.C., the Nile water flowed into it half the year, and flowed back again to the river during the other half. Strabo and Diodorus Siculus both state that the reservoir was still in action nearly five hundred years later. Somehow, and at some time since then, Lake Mœris disappeared, but the cultivated lands of the modern province of the Fayum have been identified as the bed of the ancient lake, and the low-lying Lake Kurun as the persistent rudiment of the reservoir. The existence of such a reservoir as Herodotus describes would, it is reasonable to suppose, have created conditions of flow in the deltaic branches of the river favourable to the working of a system of perennial irrigation in the lowlands of the north bordering the Mediterranean, provided only that the land level had been in those days higher than it is now with reference to sea level; and convincing evidence exists that it was so. There is also evidence to show that this land, now a barren plain, was cultivated in the past and densely populated. Numerous mounds strewn with bricks and pottery mark the sites of former towns and villages, and Rameses the Great and other Pharaohs held their courts on the Tanitic branch of the Nile at Zoan, or Tanis (now San-el-Hagar, a fishing village of the waste).

In India, the Madras native engineers introduced the system of perennial irrigation long before the East India Company

was formed. A weir across the Cauvery river in Madras, which is called the Grand Anicut, is said to have been constructed one thousand six hundred years ago—a modern work compared to the canal of Hammurabi and Lake Mœris, but still ancient enough to discourage the present generation from claiming perennial irrigation as a modern innovation; though it is modern in this sense, that it is the system which is now adopted in all new irrigation projects.

With reference to this point, Mr. Elwood Mead,[1] in his paper, already quoted, remarks: "Although modern irrigation in the United States only dates back fifty years, its practice on this continent is older than historical records. The first Spanish explorers on the Rio Grande found the Indians of that valley watering the thirsty soil, as their forefathers had done for unnumbered generations before them, and as their descendants are doing to-day. In Southern Colorado and Northern Arizona and New Mexico are well-defined remains of irrigation works, of whose origin even tradition is silent."

With this much of historical introduction, attention will now be directed to the study of the methods of perennial irrigation. There are three periods into which the evolution of a canal scheme may be divided, namely: the drawing up of the project, the construction of the works, and the utilisation of the works for the purpose for which they are constructed. These subjects will be taken in order, and the various points connected with each considered.

The project has naturally to be prepared first. Suppose, then, that for the sake of preventing famine or scarcity, or of promoting the prosperity of a country, it has been decided to resort to irrigation, and that the irrigation engineer has been called upon to prepare a project. He will first of all study the climatic conditions of the country to be irrigated, and the existing nature of its agriculture; he will then examine the soil

[1] Paper No. 33, "Irrigation in the United States," by Elwood Mead, International Engineering Congress (1904).

to determine what crops it is capable of bearing under the stimulus of artificial irrigation, and he will make himself acquainted with the configuration of the land, so as to form a general idea of the scheme of canals and drains to be elaborated afterwards.

The rainfall, as one of the climatic conditions to be studied at this preliminary stage, is that of the region which is to be irrigated, and not of the catchment area from which the water supply for the irrigation is to be derived. This latter will form the subject of later study, when it becomes necessary to consider the available sources of water supply. What the engineer entrusted with the preparation of the project first requires to know is, when and in what quantity rain falls on the area to be cultivated, with the view of ascertaining to what extent the rainfall requires supplementing by irrigation. And it is not only the deficiency of the rainfall that must be taken note of, but also its capriciousness; for it is when the climatic conditions affecting agriculture are at their worst that irrigation should prove itself a reliable insurance against loss of crops. Rainfall statistics, so far as they exist, must therefore be collected. Statistics of temperature are also necessary, as temperature is a factor regulating the intensity of the demand for water and affecting the available supply through evaporation. The quality of the soil is another factor of similar influence: light sandy soils require more water than heavy or clay soils, and the loss of water by absorption is greater with the former than the latter.

There is an important matter affecting the calculations to be made that should receive attention from the very first, as a preliminary step. If the source of supply is to be a river, and reliable records of its rise and fall and discharges do not exist, gauges should be at once set up and regular readings taken, while the discharges of the river should be measured at regular intervals, and the observations continued during the period of study, to furnish data, if no better exist, upon which calculations

can be based. The same should be done if the source is a lake: its levels should be regularly observed, and the discharge of its in-flow, or outlet channel, or both, regularly measured.

The preliminary studies indicated in the foregoing remarks relate to the demand for water. Their purpose is to furnish data upon which to base an estimate of the quantity of water required for the irrigation of the total area to be brought under cultivation. To make this estimate, we must determine the "duty" of water under the conditions of climate, soil, crops, and methods of distribution which exist, or will exist, in the tract to be irrigated.

The "duty" of water is a technical term used by irrigation engineers to signify sometimes the amount of work that water may be expected or ought to do in irrigating crops, and sometimes the amount it actually does in any one season. As the word "duty" implies an obligation, the former signification would appear to be the more correct, and will be adopted in this work. The "duty" of water may then be defined as the measure of the efficient irrigation work that water can perform, expressed in terms establishing the relation between the area of crop brought to maturity and the quantity of water used in its irrigation. The expression "efficient irrigation work" implies that the water supplied to the crop is neither more nor less than what is best for it.

The relation between water and crop can be stated in various ways according to the unit of measure selected. The "duty" may be represented as the area of crop matured by a given quantity of water flowing continuously; or as the quantity of continuous flow required to mature a given area of crop; or as the total volume required for a given area of crop.

In India the measure of the "duty" is expressed in terms of that area of crop which a discharge of 1 cubic foot per second (abbrev. 1 cusec), flowing continuously during the life of the crop, is able to bring to maturity. This same form of expression is also used in America when considering the flow of a

stream, with, however, "second-foot" as the abbreviation for 1 cubic foot a second. But when the contents of a storage reservoir, for instance, is in question, the "duty" of water is sometimes expressed in terms of the volume of water which will cover an acre to a depth of 1 foot, and which, therefore, equals 43,560 cubic feet. This unit of volume is called an "acre-foot." The storage capacity of a reservoir is given in America as so many "acre-feet," whereas in India the content would be given as so many million cubic feet, and in Egypt as so many million cubic metres. The "acre-foot" unit has this advantage among some others, that it bears a direct relation to the unit used in defining areas of cultivation, and it is more convenient for comparison with rainfall figures which are given in inches of depth. It is also more suitable than cubic feet when large volumes have to be represented by figures, as, for instance, when considering such matters as the annual storage of the Great Lakes of the St. Lawrence basin, which is calculated to reach a figure of 2,419,000,000,000 cubic feet.

The relation between the two terms—1 cubic foot per second (cusec, or second-foot) and 1 acre-foot—is as follows:—One cubic foot per second flowing for twenty-four hours will cover an acre nearly 2 feet (1·98) deep; that is, it delivers an amount equal to nearly 2 acre-feet. If the acre-foot is used as the term of expression, the "duty" is that number of acre-feet required to mature an acre of crop.

In Southern Europe the "duty" is stated as so many litres, or sometimes cubic metres, per second per hectare. In Egypt the "duty" is similarly expressed in terms of a continuous flow, namely, as that discharge in cubic metres per day of twenty-four hours, flowing continuously during the life of the crop, which is required per acre. It is also sometimes expressed in the form used in India, with cubic metres substituted for cubic feet, the "duty" then being the number of acres of crop which 1 cubic metre per second, flowing continuously during the life of the crop, can bring to maturity.

There is yet another unit of quantity used in the United States West, known as the "miner's inch." It is a little uncertain in value, as it varies according to the method of measurement. In California it represents a fiftieth part of a second-foot, in Arizona a fortieth.

The "duty" of water is said to be a high or a low one according as a given quantity successfully irrigates a large or a small area.

The different methods of expressing the "duty" of water have each points to recommend them, according to the object of the calculation in which the "duty" forms one of the factors. Thus, if it is desired to determine the area of crop that a known discharge can irrigate, it is convenient to have the "duty" expressed as the area that a continuous discharge of 1 cubic foot, or 1 cubic metre, a second can irrigate. If, on the other hand, the calculation of the discharge required for the irrigation of a given area is being worked out, it is more convenient to have the "duty" expressed in the form most used in Egypt, namely, as the number of cubic metres required to irrigate an acre. The acre-foot, it has already been pointed out, is a convenient form to use in calculations relating to large storage works.

As the "duty" of water, or the measure of its power of doing work, is the basis of all calculations in the design of an irrigation project, it may be well to show by a simple example how the "duty" may be arrived at. Let it be assumed that the conditions of climate and soil, and of crop requirements, are such that waterings are required at intervals of eighteen days, and that each watering is equal in volume to the quantity represented by a depth of 3½ inches over the land surface. An acre has a superficial area of 43,560 square feet. Each watering will therefore require a quantity of $\left(\frac{3\frac{1}{2}}{12} \times 43{,}560 =\right)$ 12,705 cubic feet per acre at the field. If it is desired to calculate the "duty" of water at the canal head, so as to determine what quantity the main

canal must draw in from the source of supply, an allowance must be made for loss of water between the canal head and the field. What this allowance should be depends upon many things. The loss is rarely less than 30 per cent., and may even amount to as much as 70 per cent. when the conditions are unfavourable to economy. It is due to evaporation and absorption in the carrying canals and to waste in the fields. The condition of the canals, and the degree of skill and care applied by both engineers and cultivators to the distribution of the water, has great influence on the amount of the loss. Evaporation, moreover, varies with temperature and with the humidity of the atmosphere; absorption with the soil; and both with the distance that the water has to travel between the source and the crop. The calculations must therefore admit the inevitable coefficient that varies with the particular conditions of each case, and so introduce the element of individual judgment which is so liable to err. However, there is no help for it.

The percentage of loss by absorption is greater in new canals than in old ones in consequence of the staunching action of silt deposit both on the bed and slopes. The absorption naturally bears a direct relation to the extent of the surface of the bed and slopes with which the water is in contact. Recognising this, the engineers of the Punjab, in India, use this area as the basis of their estimate of the quantity absorbed, assuming a loss of 8 cubic feet a second per million square feet of wetted surface.

From experiments made on the Ganges and Bari Doab Canals in India, the following conclusions as to the loss of water from evaporation and absorption in running canals, between the source of supply and the crop, were arrived at. Of the volume drawn in at the canal head—

15 to 20 per cent. is lost in the canal;
6 to 7 per cent. ,, ,, ,, ,, distributaries;
21 to 22 per cent. ,, ,, ,, ,, village water-courses.

It was further held that half of the remainder was wasted in

various ways by the cultivators, mainly in excessive irrigation. This is evidently somewhat of an assumption, and, in any case, the figure arrived at by actual experience, as that which represents the "duty" of water, will cover this waste, if waste there is. It is not reasonable to expect such economy on large irrigation systems as is obtainable when each plant is served by a watering pot.

If the loss between the canal head and the crop is assumed to amount to 40 per cent. of the discharge entering the canal head, the estimate of water required is completed as follows, it having already been found that the quantity required at the field for a single watering of 1 acre is 12,705 cubic feet. If Q is the quantity drawn in at the head, its value will then be found from the following equation

$$Q - \tfrac{40}{100}\,Q = 12{,}705 \text{ cubic feet:}$$
$$\text{whence } Q = 21{,}175 \text{ cubic feet.}$$

This is the quantity required per acre of crop once every eighteen days; or, in other words, a continuous discharge at the canal head of 1,175 cubic feet per day is required for every acre of crop. This is one way of expressing the "duty."

There is next to be determined the value of the "duty" expressed in the area irrigated by 1 cubic foot a second. To arrive at this, the calculation must be made of the number of times a discharge of 1 cubic foot a second, flowing for eighteen days, will give the quantity required for a single watering of 1 acre, namely, 21,175 cubic feet. A discharge of 1 cubic foot a second gives 86,400 cubic feet a day, or 1,555,200 cubic feet in eighteen days; and is therefore sufficient to irrigate

$$\frac{1{,}555{,}200}{21{,}175} = 73{\cdot}44 \text{ acres.}$$

Hence, under the conditions assumed, 73·44 acres is the "duty" of the supply at the canal head.

The results of actual experience will now be given.

In India the "duty" varies considerably, as might be expected

in a country where the conditions affecting it have so wide a range of variability. There are two crop seasons in India, known as the *kharif* and the *rabi*. The *kharif* season includes the period of heavy rain, which may be said to extend, generally, from the middle of June to the middle of October; the *rabi* season is the period of cold weather, November to March. The crops of the *kharif* season are, in the United Provinces and the Punjab, maize, indigo, cotton, and other crops, with a small proportion only of rice; in Bengal they are almost entirely rice. The crop of the *rabi* season is mainly wheat. As a rough average it may be reckoned that 1 cubic foot a second will irrigate from 140 to 160 acres of *rabi* crop, and 70 to 80 acres of *kharif*.

In Egypt the "duty" has been worked out carefully for the summer crops only, of which sugar-cane and cotton are the most important; and it has been assumed that rice (also a summer crop) takes double the amount of water that the other crops do. During the life of these crops no rain falls, so that they are entirely dependent on the canals for the water necessary to their growth. As the result of observations made during a succession of summers of very low supply in the Nile, the conclusion was arrived at that an allowance of water at the rate of 30 cubic metres a day per acre of summer crop, and double that amount for rice, is sufficiently liberal to provide a watering every eighteen days for cotton, sugar-cane, &c., and every nine days for rice; or, in other words, 1 cubic metre per second is sufficient for 2,880 acres of summer crop, or half that area of rice. This is equivalent to saying that 1 cubic foot a second will irrigate 81½ acres of summer crop, or half that area of rice. In Egypt it has been found that 40 per cent. of the gross area is annually put under summer crop. The "duty" above stated, of 30 cubic metres a day, is per acre of crop; if this is converted into the "duty" per acre of gross area, the figure becomes 12 cubic metres. If, then, the area commanded by the canal system—which in Egypt is identical with the gross area—is

1,000,000 acres, the discharge required to be drawn into the main canal from the source of supply is 12,000,000 cubic metres a day during the life of the summer crops.

In the perennially irrigated tracts of Egypt it is reckoned that nearly all the land is under crop during the flood season, 40 per cent. being cotton and the remainder maize. For the flood season an allowance of 25 cubic metres a day per acre of gross area is the accepted figure. The levels obtainable in the flood season being higher than at other times, the increased discharge can easily be supplied. By a system of distribution that is favourable to agriculture both in the flood and summer season (to be described later) the canals are made to carry the summer and flood discharges with convenient surface levels, though one is nearly double the other in volume.

As regards the rice crop in India, irrigation engineers have practically accepted 50 acres at the head of the canal system as the "duty" for a continuous discharge of 1 cubic foot a second, allowing a period of about twelve days for irrigating the whole area of crop. In Eygpt, when the intervals between waterings are fixed at nine days, the duty is 42 acres for the same discharge. If this latter period were to be extended to eleven days, the "duty" would rise to 51 acres. As the period in India is given as *about* twelve days, it may be said that both India and Egypt are agreed upon this point.

It is interesting to find that the recent experience of irrigation in India and Egypt has led to the same conclusion as that reached by Italian engineers fifty years ago. It has been stated above that in Egypt 1 cubic foot a second will irrigate 81½ acres of summer crop, or half that area, say 42 acres, of rice. Now Baird Smith, in "Italian Irrigation," 1855, Vol. II. p. 66, states that, "According to the best Italian authorities, 1 cubic foot per second is sufficient for the irrigation of from 35 to 40 acres of rice"; and adds, "This is fully twice the quantity required for ordinary meadow irrigation." He also, when summing up, comes to the conclusion that, "under ordinary

circumstances, the effective power per cubic foot per second is 93 acres."

Sir Colin Scott-Moncrieff, in his "Irrigation in Southern Europe," 1868, presents a Table on p. 33 which gives, for the south of France, a mean "duty" of 83·4 acres, watered during the six months of irrigation, for a continuous discharge of 1 cubic foot per second, with seven to fifteen day intervals between waterings.

Wilson, in his "Irrigation Engineering," 1903, gives the following information concerning "duties" in the United States:—"The State engineer of Colorado now accepts 100 acres per second-foot as the "duty" for that State, varying on the supply at the head from 70 to 190 acres. In Utah 70 to 300 acres per second-foot is the duty. In Montana it is about 80 acres per second-foot."

In Southern California the "duty" obtained is very high. For surface irrigation it is 150 to 300 acres; for sub-irrigation from pipes 300 to 500 acres. So high a "duty" is only to be obtained by the use of cemented channels and pipes for carrying the water, and probably only in the case of orchard cultivation.

Newell, in "Irrigation," 1902, p. 214, states: "It is frequently estimated that 1 cubic foot per second, or second-foot flowing through an irrigating season of ninety days, will irrigate 100 acres." This, as a rule of thumb, would be a convenient one, but, in the case of *kharif* in India and summer crops in Egypt, 70 to 80 acres would seem to more accurately represent the average "duty."

In a report on the best method of utilising in irrigation the waters of the River Guadalquivir, made in 1906 by Mr. R. B. Buckley and the author of this work for the Spanish Government, the "duty" adopted in the projects recommended was 1 cubic metre per second for every 2,000 hectares of winter crop, and for every 1,000 hectares of summer crop. This is equivalent to a "duty" of 140 acres in winter and 70 acres in summer for each cubic foot of discharge per second. In the

same report the duration of the irrigating seasons was reckoned as six months for the winter crop and four months for the summer crop.

When the engineer entrusted with the preparation of a project has, after consideration of all the conditions affecting the question, decided on the "duty" for each crop or season, and has ascertained the areas under crop in the different seasons, and the periods for which each crop requires irrigation, it is then a simple matter to calculate with these data the discharges required throughout the year, or the quantity of water that it is necessary to store annually. If it is the continuous discharge of a canal which it is desired to determine, the duration of the life of the crop does not affect the calculation. If, for example, the "duty" for a particular crop or season is 80 acres per cubic foot of discharge per second, the discharge required for 10,000 acres of crop will be $\left(\frac{10,000}{80}=\right)$ 125 cubic feet a second flowing continuously for the period during which the crop requires irrigation, whatever that period may be. If, on the other hand, it is desired to calculate the total volume of water required to bring a crop to maturity, as may be necessary in considering the question of storage, the period of flow is a necessary factor. In India this period is technically known as the *base* of the "duty." Taking the same example as before, if the "duty" is 80 acres per cubic foot per second, and the area of crop 10,000 acres, and the time during which it requires irrigation one hundred days, the total volume required to mature the crop will be $\left(\frac{10,000}{80}\times 86,400\times 100=\right)$ 1,080,000,000 cubic feet. In this case the "duty" of the water of the reservoir may be expressed as 108,000 cubic feet per acre, implying that, on the average, each volume of 108,000 cubic feet of water drawn from the reservoir is sufficient to mature 1 acre of crop. An addition to the total volume required to

mature the crop must be made to allow for evaporation and absorption in the reservoir itself, in order to arrive at the total quantity of storage necessary. In this example it is assumed, in the first case, that the "duty" used is that at the head of the canal, and in the second case at the reservoir outlet.

The amount of irrigation work that canal water actually does—or, rather, is shown in annual reports as doing—varies from year to year in consequence of the rainfall not being a constant quantity. The explanation of this is that the canal water is credited with the work done by the rain. This accounts for the great variation in the so-called "duty" (signifying work actually done) which appears in the annual irrigation reports of India for any particular canal. Taking, for example, the November figures of the Bari Doab Canal for ten years, the "duty" (work actually done) of 1 cubic foot a second varies from 111 to 222 acres, the average being 169 acres. From the statistics of work actually done by water, the amount of work which it may be expected to do, under either normal or extreme conditions as may be desired, is determined. In the particular case of the Bari Doab Canal, the accepted "duty" for the *rabi* season, representing the work that ought to be done, is 160 acres to the cubic foot per second. The statistics of the month of November were selected for ascertaining the "duty," as November is the month in which the *rabi* sowings are principally made, and the "duty" which can be obtained in that month may determine the area of crop which can be sown.

Mr. Buckley points out that it is the "duty" of the "period of pressure," or greatest demand, and not of the whole irrigating season, which is the important "duty" to determine. "The 'duty' of water drawn in at the head of a system is a useful factor in many ways, but it is often most desirable to gauge it at other points in the system, and with reference to different 'bases,' that is, to shorter periods of time than that

of the whole irrigating period of a crop; for the 'duty' based on the discharge drawn from the source of the supply on the average of the whole season fails to take cognisance of fluctuating demands. It is necessary in most cases to know not only the average discharge of a season, but the maximum discharge required at a period of pressure during the season."

The summer "duty" of water in Egypt is not calculated from the whole irrigating period of a crop, but from the period during which the whole available supply in the Nile is utilised and it is found necessary to apply rotations to secure a fair distribution of water. The duration of the latter period varies from seventy to one hundred days. If any longer period is used for the calculation of the "duty," such, for instance, as the life of the crop, the "duty" would appear less than it should, in consequence of surplus water, that was doing no work, not being eliminated from the calculations.

Similarly, when rain supplements artificial irrigation, the "duty" appears higher than it should do, as the watering done by the rain is credited as work done by the canal water.

CHAPTER IV.

SOURCES OF SUPPLY.

THE preceding chapter deals with the considerations that regulate the demand for irrigation water: the present chapter relates to the question of supply.

Rainfall is the primary source of all water supplies; but if rain does not fall when or where the need of water is felt, then artificial means must be devised to keep it in hand when it does fall, till it is wanted, or to carry it to the place where it is required, unless Nature has undertaken to do both. Rivers are Nature's waterways which carry the rain-water that falls in their catchment areas to regions where, may be, no rain falls. The case of the Nile and Egypt has already been cited as a well-known example. But the open channels of rivers are not the only natural carriers, though they do by far the heaviest part of the work. Water travels also by ways unseen, in closed channels underground, confined between watertight strata, and feeds springs and wells, often at great distances from the starting-point. Such a natural arrangement fulfils both duties; it not only provides for carrying the water to the places where it is used, but for holding it in reserve till it is drawn upon.

This underground supply, when utilised for irrigation, is tapped chiefly by wells fitted up with some form of lifting apparatus. From the point of view of agriculturists well-irrigation is an important matter. It has been estimated that, of the 44,000,000 acres under irrigation in British India in 1903, 13,000,000 acres were irrigated from wells, of which there were probably 2,500,000.

In Egypt well-irrigation has less importance, and will have

less and less as the canal system becomes more perfect. There are some 30,000 wells still used for irrigation in Lower and Upper Egypt.

In California there are about 150,000 acres served by wells, the artesian conditions of the Californian valley being exceptionally favourable to this form of irrigation. There are said to be 8,097 artesian wells in the State.

Important though well-irrigation may, therefore, be held to be as an aid to agriculture, the construction of wells and the management of the irrigation effected by them are matters which are not generally considered to lie within the province of the irrigation engineer. They have hitherto been left to private enterprise, and the farmer would probably prefer to have it so. For, as Sir Colin Scott-Moncrieff pointed out in his Address to the Engineering Section of the British Association, 1905, "there is one practical advantage in irrigating with the water raised from one's own well, or from a river—it is in the farmer's own hands. He can work his pump and flood his lands when he thinks best. He is independent of his neighbours, and can have no disputes with them as to when he may be able to get water and when it may be denied to him." But, though well-irrigation can be made a profitable farming operation for any class of crop when carried out by cultivators who work on the land themselves and use their own cattle, it is otherwise an expensive method, and can only be made to pay by cultivating the more valuable kinds of crops. Moreover, it would seem to be out of favour with those who have had experience of both canal and well water. Mr. Buckley remarks: "The superiority of the rain-water over that of wells is demonstrated by the fact that near the heads of the Punjab canals the cultivators prefer to pay canal rates and to lift the water from the canals rather than to lift it from wells, although the canal level and the spring level are about the same." On the other hand, during the cold weather, well water is given the preference on account of its higher temperature as compared with canal

water. To this day the opium cultivators of Behar, a district of India, lift water from their wells rather than run it on to their fields from the canals.

Rivers are the principal sources from which the irrigation engineer draws the supply of water required to feed a canal system. Some rivers are fed by rain, others by snow. If they are fed by rain, the rise and fall of the river will respond to the rainfall more or less faithfully according to the remoteness and nature of the catchment area in which the rain falls, if no lakes intervene to affect the forward flow. If the rivers are fed by snow falling on mountain heights where their sources lie, the rise of the river will commence when the summer heat causes the snow to melt. The snowfields that feed certain rivers are Nature's reservoirs for the storage of water till the summer comes. And, moreover, such reservoirs are automatic in their action, for, the greater the heat, the greater will be the want of water for irrigation, and the more plentiful the discharge from the melting snow. This convenient arrangement produces conditions favourable to the working of a system of perennial irrigation. The Indus and other rivers of Upper India are snow-fed. So, also, is the Tigris; but Mesopotamia is still waiting for the generation to be born that will take advantage of the gifts that Nature offers and restore to the land of the twin rivers its former prosperity.

There are some rivers which have lakes for their sources, the lake basins serving as collecting reservoirs for the rain which falls in their catchment areas. Rivers so fed do not exhibit the same fluctuation of levels as rivers that have no such collecting basins to operate as moderators. The largest group of natural reservoirs in the world are the great lakes of the St. Lawrence basin above the Niagara Falls, which have a surface area aggregating nearly 88,000 square miles, and a catchment of 265,095 square miles. The mean annual fluctuation of the levels of these lakes is very nearly 1 foot. A layer of 1 foot depth over the lake area of 88,000 square miles would contain 2,453

billion cubic feet, sufficient to produce a discharge of 76,500 cubic feet a second for a year. In consequence of the great regulating action of these lakes, with their enormous storage capacity and evaporating surface, there is no such thing as high and low water recognised on the river below. The wealth of water carried by the St. Lawrence river pursues its way to the Atlantic through the humid region where the rainfall is copious—usually from 40 to 60 inches per annum, or even more—so that it is not agriculture that benefits by the constancy of the river discharge, but navigation only. For in the eastern half of the United States it is drainage and not irrigation that requires attention.

There are in Europe also natural reservoirs which act with similar effect to the St. Lawrence lakes, but they are on a very much smaller scale. The Po discharge has a constancy due to the fact that it is drawn from Lakes Como, Maggiore and Garda; the Rhone is moderated by the influence of Lake Geneva, and the Rhine by Lakes Constance and Neuchatel. The aggregate area of the surfaces of these six lakes is less than one hundredth part of the area of the St. Lawrence lakes above the Niagara Falls.

The Yenisei river, in Siberia, is fed by the Baikal lake, which has an area of 12,430 square miles.

The equatorial lakes of Africa are the most worthy rivals of the St. Lawrence lakes in respect of the aggregate surface area of the group, but their influence is divided between three rivers. There is Lake Nyassa, of 9,000 square miles area, at the source of the Shiré, a tributary of the Zambesi; there is Lake Tanganyika, of 12,650 square miles, together with smaller lakes, at the source of the Congo; and the Victoria, Albert and Albert Edward Nyanzas, of 29,000 square miles aggregate area, at the sources of the White Nile. The Nile lakes certainly exercise a moderating effect on the fluctuations of the White Nile, but, unfortunately for Egypt and the Sudan, the moderating influence is carried too far, as the lakes not only act as collecting and storage

basins, but as evaporating tanks as well, with surfaces so extensive in relation to their catchment areas that an excessive proportion of the rainfall is lost by evaporation. And this loss is increased to a serious extent in the enormous swamps known as the Sudd region, which the water has to traverse on its way to the North. Evaporation from the water surface of these marshes and absorption by water plants reduces the discharge of the river by more than a half.

However beneficial as moderators of extremes of high and low discharges natural reservoirs may be, it is seldom that they act conveniently in all respects without artificial control. In the interests of navigation an extensive system of artificial reservoirs has been constructed out of some of the many lakes at the sources of the Mississippi river. Another fine example of such reservoirs exists in Russia at the interlacing sources of the Volga and the Msta rivers. By the water stored in these reservoirs, which comprise several lakes, the navigability of the two rivers is maintained during the season of low water ; and, with the help of an artificial waterway, the Volga is connected with the Msta, and thereby the Caspian with the Baltic.

But instances of natural lakes under artificial control serving rivers on which irrigation systems depend are rare. One such instance there is on record, but the lake as an effective reservoir is now extinct. Mention has already been made of Lake Mœris as described by Herodotus. He was told by his guide that the lake was an artificial one, and it seems that he believed it. But he need not have done so, as the guide had no possible means of knowing how the lake came into being, several thousand years before he was born There is little doubt that the crops of the modern Fayum Province are grown on the bed of the ancient lake. The lake would have had a surface area of about 700 square miles, and a superior layer of about 10 to 15 feet depth of water which could have been used to supplement the river in summer. It was not situated at the Nile sources, but some 3,000 miles below them, and about 60 miles above the apex of

the Delta. Neither was it in the track of the river itself, for it lay just outside the Nile valley, but was connected with the river by a short branch, like a bud on its stalk. In this situation it was most conveniently placed to act as a moderator of fluctuations of level in the Deltaic branches of the river. This natural reservoir was brought under control by regulators constructed on the channels of in-flow and out-flow, so that the flood water could be admitted to the lake to the extent desired, and the stored water be returned to the river when it was wanted. Possibly this reservoir also was worked in the interests of navigation only, but, as has been already suggested, it may have also promoted the former prosperity of the northern margin of the Delta by providing a sufficient supply of water for cultivation at other seasons of the year than that of flood.

The Lake Mœris reservoir was in a peculiarly favourable situation for moderating high floods and supplementing low summer discharges in the Deltaic branches of the Nile. Usually the lakes which act as natural reservoirs to rivers are located near their sources, at a distance, sometimes very great, from the point where any beneficial effect from their action would first be felt. One great disadvantage resulting from the distance is that much of the stored water is lost by evaporation and absorption during its flow. Another drawback is the difficulty of regulating the supply from the reservoir so as to give the exact amount required at a distant point, where the effect of any alteration of the reservoir out-flow would not be felt for many days after.

In the absence of natural lakes, artificial reservoirs must be made if storage of water is to be effected.

The question of storage may either arise during the period of design, or after a canal system has been some time in operation. An artificial reservoir may be the essential feature of the original irrigation project, and may be required to serve either as the sole source of supply, or as supplementary to a river of deficient discharge. But the necessity of a supplementary

reservoir is not always recognised during the period of designing an irrigation system. More often the necessity of supplementing the river discharges by storage does not make itself felt until the effect of the irrigation, carried on with the natural discharge of the river, has reached its full development and the demand for water has increased in consequence of an unforeseen expansion of the area brought under cultivation. The recent history of irrigation in Egypt provides an interesting example of the latter conditions. In 1884 the newly appointed irrigation engineers from India commenced the work of reform of the irrigation works in Egypt, which they and their successors have carried on steadily ever since. As the reform in means and methods took effect, the cultivation became more intense and the area wider, until at length every drop of the summer discharges of the Nile was utilised, and no further development of cultivation was possible without an addition to the summer supply of the river. During the flood and winter seasons, however, there is always enough water and to spare in the river, so that there is a surplus available in those seasons for storage. The further development of Egypt could, therefore, be promoted by the creation of a reservoir capable of holding this surplus water in reserve for the summer months. The study of projects for its storage was, therefore, undertaken.

The first calculation to be made, in the particular case selected as an example, was one to determine the quantity of water that it was necessary to store in order to be able to supplement the summer discharges of the Nile to such an extent that Egypt might receive its full development. This calculation made, it remained to decide to what extent the first reservoir should provide for this, and also to ascertain whether there was a sufficiency of surplus discharge to furnish the quantity to be stored, without inconvenience to navigation and other interests affected. To determine the quantity of storage required, the first thing to do was to calculate the total requirements of Egypt. Experience has shown that an

allowance of 12 cubic metres per day per acre of gross area gives a sufficient supply for summer cultivation. In round figures the area of Egypt, including areas to be reclaimed and exclusive of 500,000 acres to be permanently maintained as basin land, may be taken as 7,000,000 acres. Consequently the total daily discharge required in summer is 84,000,000 cubic metres. The natural summer discharge of the river may be taken as 24,000,000 cubic metres a day. Therefore 60,000,000 cubic metres a day is required from the reservoir for, say, one hundred days, making a total quantity to be stored of 6,000,000,000 cubic metres. No deduction is here made for evaporation in the reservoir, as the summer discharge during the greater part of the hundred days is considerably greater than 24,000,000 cubic metres a day, and the quantity in excess of that discharge may be considered as balancing the loss by evaporation.

It was necessary, also, to decide the best site for the first reservoir to be made and its storage capacity. At the time that these questions were being considered, the Mahdi was in power on the Upper Nile, and the examination of reservoir sites was restricted to the river below the second cataract. In consequence of this limitation of the area of survey, Egypt has probably benefited by getting its reservoir some years sooner than it otherwise would have done. For, if the Upper Nile had not been closed to him, Sir William Willcocks, who was in charge of the reservoir study, would certainly have required more time for the examination of other sites higher up the river, and he would, doubtless, have come to the same conclusion in the end. For there is probably nowhere on the Nile a more favourable site for the construction of a dam than the crest of the first cataract above Assuan, not only on account of the quality of the rock and the disposition of the summer channels, but also on account of the site being the nearest possible one that could serve both Upper and Lower Egypt. If, then, Sir W. Willcocks' studies showed that the storage capacity of a reservoir which could be created by the construction of a dam

at Assuan was sufficiently ample, there was everything to recommend the project, one thing only excepted, and that the resulting submersion of the island of Philæ. The basin of the Assuan reservoir is the valley itself through which the Nile runs. Bounded by high rocks, it is of little width; consequently, to have capacity, the reservoir had to be deep. Cross-sections of the valley were taken to determine what the capacity of the valley was with different water-levels, in order to furnish data for a decision as to the height to which the Assuan dam should be built. It was calculated that a dam holding up water to 16 metres above the natural low-water level would create a reservoir capable of storing 1,065,000,000 cubic metres; and that if the dam were made 12 metres higher, the reservoir capacity would be increased to 3,733,000,000 cubic metres. Eventually it was proposed to build a dam to hold up to 24 metres above low water, and thereby to create a reservoir with a storage capacity of 2,550,000,000 cubic metres. But Egypt was not to be allowed to go so fast. Strong protests from the archæological societies of Europe extracted a reluctant compromise from the Government of Egypt, and the lower dam design, which provided a storage of 1,065,000,000 cubic metres only, was adopted. Europe has often interfered in the affairs of Egypt, not always with advantage to the dwellers on the Nile, and, in this case, with little satisfaction to itself. At the time of making this compromise it was calculated that the total quantity of water required to be stored to supply the needs of all Egypt and provide for its full development was 3,610,000,000 cubic metres, so that the Assuan reservoir, as decided on, would hold less than a third of the total then supposed to be required. The figure for all Egypt is now considered to be 6,000,000,000 cubic metres, of which the Assuan reservoir provides 1,000,000,000, leaving 5,000,000,000 still to be arranged for.

As the sources of supply for an irrigation scheme are being considered, and Egypt furnishes a concrete example of a country

seeking means to still further increase its water supply, it may be interesting to examine the suggestions which have been made to obtain that increase. There are five possible ways of doing it :—

(1) The Assuan dam might be raised, and the capacity of its reservoir doubled;

(2) Another dam, similar to the Assuan dam, might be built on the river at some suitable point higher up, to form another reservoir in the Nile valley itself;

(3) A reservoir might be created in a depression known as the Wadi Rayan, alongside the Fayum province, which would be close to the site of Lake Mœris, and would act in much the same way as the ancient reservoir, though it would be on a smaller scale;

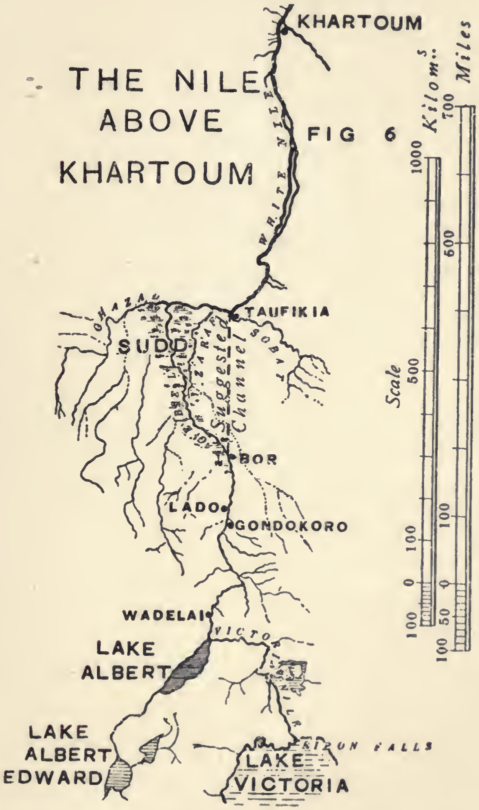
(4) The loss by evaporation and absorption, where the river spreads itself out through the Sudd region, might be enormously reduced;

(5) The lakes near the equator at the White Nile sources might be controlled by regulation so as to serve as storage reservoirs.

Enough has already been said about the Assuan reservoir and Lake Mœris to show in what way the first three alternative projects would provide for feeding the river at low supply, and on what data the calculations concerning their utility would be based. The fourth method of increasing the supply, by diminishing the loss due to evaporation and absorption, is an unusual one, and the proposal is the outcome of the peculiar conditions of the Upper Nile above Khartoum.

On the long line of river lying between the equatorial lakes and Khartoum (see Fig. 6) the swamps, known as the Sudd region, are traversed by the flowing water for a distance of nearly 500 miles. In these swamps the river spreads itself out over a vast area of unknown extent, escaping sideways from the two more or less well-defined channels into which the river divides itself where it enters the marsh tract. Over this expanse

of water-surface evaporation is active, while the papyrus and other swamp-loving plants, stretching away in all directions without visible limits, have a power of absorption proportional to the vast extent that they cover. Discharge observations have shown that, of the water which enters at the upper end of the



swamps, 50 per cent. is lost in summer and 75 per cent. in a high flood. The actual measurements give the following results. During summer the discharge entering the swamps at Lado is 600 to 700 cubic metres a second, of which only 300 finds its way out at the lower end of the Sudd region. In a low flood the discharge entering is 1,000 cubic metres a second,

of which 400 reappears; in a high flood 2,000 enters, and 500 comes out again.

If, then, this loss could be entirely prevented, the summer discharge of the river could be increased from 300 cubic metres a second to 600 at the point where it leaves the swamps. This would represent an increase of 26,000,000 cubic metres a day (over 10,000 cubic feet a second), which would go a long way towards making good the present deficiency of the water supply of Egypt; for the increase would be equivalent to that which would be obtained from a reservoir storage of 2,500,000,000 cubic metres. One great advantage in this method, over that of storage in reservoirs, is that the river supply is not decreased at any time of the year in order to obtain an increase at another, but is increased at all seasons, a matter of some importance when the quantity still required to supplement the river in summer reaches such a high figure as 5,000,000,000 cubic metres.

The method proposed, with the object of diminishing the enormous loss of water in the Sudd region, is to form an embanked channel from end to end of the swamps in order that the river discharge may be prevented from spilling sideways except at such times and places as may be found desirable. It would not be economical or even advantageous to form a channel large enough to carry the flood discharge; therefore some provision would have to be made for disposing of the surplus water. The original suggestion was to construct regulating works at the head of the proposed channel, so that only the required discharge should be allowed to flow into it, and the surplus be escaped through masonry sluices to spread about at will in the swamps and be evaporated and absorbed. But a later, and probably better, proposal has been made for the disposal of this surplus, and that is, to prevent it from leaving the upper lakes at the river sources, and so to keep it in reserve till it is wanted. The area of the lower and smaller lake, the Albert Nyanza, is so great that a regulating work at

its outlet, designed to hold up not more than 3 metres (10 feet), would probably give all the control necessary. The regulation of the outflow of Lake Albert is another matter connected with the storage question. At present the subject under consideration is the method of adding to the available supply in the lower reaches of the river by the avoidance of loss in the upper reaches. In the example selected for illustration the means of prevention consists in arrangements to lessen the waste by the confinement of the discharge in a channel of uniform section adapted to its volume. In the particular instance of the Nile swamps the difficulty lies in selecting the most favourable alignment for the channel, and in executing the work when the line has been chosen. Either an existing channel must be enlarged and embanked, or a new canal and banks be made along whatever alignment may be found to be the most favourable. The shortest distance possible would be that of a straight line joining the river at Bor with the point where the Sobat river ends in the White Nile, the length of which is 210 miles, as shown in Fig. 6. The distance between the same points, following the windings of the existing principal channel, is 440 miles, or more than double the distance along the straight line. The length of channel to be formed must, therefore, be something between 440 and 210 miles. This would in any case be a formidable undertaking, but it is one which, if it proved successful, would fully justify a very high expenditure. But though the loss of water may be materially decreased, it cannot be entirely prevented, as there must be some considerable loss from evaporation and absorption in a canal of 300 miles length, more or less, lying wholly within the tropics. Even if there were none, and the discharge at the head reached the tail in undiminished volume, the full requirements of Egypt would still not be met, and additional storage somewhere would be necessary.

If one or more of the three alternative projects of storage already enumerated is not selected to supply the deficiency,

there still remains the fifth alternative of controlling the water that leaves the equatorial lakes. That the lowest lake of the three, the Albert Nyanza, has capacity enough to store all that is wanted with a heading up of a few feet only, is easily shown. The surface area of the lake is 4,500 square kilometres. Before the Assuan dam was made Egypt was in need of 6,000,000,000 cubic metres of stored water for use in summer. The Assuan reservoir supplies 1,000,000,000. The formation of an embanked channel through the swamp region would effect an increase of the summer discharge equivalent to that produced by a storage of, say, 2,000,000,000 cubic metres. Consequently a further storage of 3,000,000,000 cubic metres is required. It is difficult to estimate what proportion of such an increase would be lost on the long journey (some 3,000 miles) from the lakes to Egypt, but it would not be very great, as a moderate addition to an existing supply would only slightly increase the evaporating and absorbing areas. Hence, if 4,000,000,000 cubic metres of storage is effected, it may be considered that sufficient allowance has been made for loss on the way. The area of Lake Albert being 4,500 square kilometres, or 4,500,000,000 square metres, a layer of 90 centimetres (or 3 feet) depth would represent a stored volume of 4,000,000,000 cubic metres; and that is what is wanted.

It has now to be ascertained if the quantity of rain that reaches the lake from the gathering ground is sufficient to provide for that storage. There are, in this particular case, two ways of calculating what the quantity available for use is. The one method is to calculate the quantity from what flows into the lake from the gathering ground; and the other, and more accurate method, is to make the calculation from what leaves the lake. As reliable data for making the calculation by the former method do not exist, the second method alone can be usefully applied to this case. The mean discharge of the Albert Nyanza outflow for the year, measured in the river

below the outlet of the lake, is officially given as 769 cubic metres a second. Assuming that the numerous torrents which feed the river between the lake outlet and the head of the proposed new channel give a sufficient discharge without any help from the lakes for the four months of high supply, the volume of the discharge of the Albert Lake outlet could be entirely stored in the lake for these four months, and be added to the normal discharge during the remaining eight months. The quantity stored would be at the rate of 769 cubic metres a second for four months, and the addition to the normal discharge for the remaining eight months would, therefore, be half that figure, or 384 cubic metres a second, equivalent to 33,000,000 cubic metres a day, or a storage of 3,300,000,000 cubic metres for use during the low supply period of one hundred days. So it may be concluded that, if the data are correct, the storage possibilities of the equatorial lakes are barely sufficient to satisfy Egypt, even after the Sudd channel has minimised the loss in transit through the swamps.

With the help of illustrations borrowed from the Nile, the following instances of water supply have been passed in review: firstly, a supply derived from the natural discharge of a river unaided by any reservoir; then, of a river with a lateral reservoir to supplement its lower branches; again, of a river supplemented by a reservoir made in the valley of the river itself far below its sources; then again, of a river discharge being increased by prevention of waste on the line of flow; and lastly, of a river fed by natural reservoirs brought under control by engineering works of regulation. There remains one more class of reservoirs, of which the Nile furnishes no example, but which is perhaps the most common in other countries. This class includes artificial reservoirs made in the upper part of the catchment of a river. Such a reservoir is formed by the construction of a dam on the most convenient site—usually across a gorge—whereby the discharges of the

higher tributary streams are intercepted and retained in the valley which is converted into a reservoir by the dam.

The Indian Irrigation Commission (1901—1903) in its report, among other recommendations for storage works in many parts of India, proposes, in the interests of the Deccan districts of Bombay, "that the catchment areas of all the rivers which derive their supplies from the unfailing rainfall of the Western Ghâts should be carefully examined with a view to the construction of as many large storage reservoirs as possible, and of the works necessary for carrying the supply into those tracts in which irrigation is most urgently needed."

Sir Thomas Higham, who was one of the members of the Indian Irrigation Commission, stated in the discussion on Irrigation, St. Louis Exhibition Congress, 1904, that "almost all future extensions of irrigation in India, with the exception of the large canals that are still possible in Northern India and in Sind, will involve the construction of storage works."

In the United States further progress in the irrigation of the arid regions can only be brought about by the storage of flood waters in reservoirs. For nearly the whole available flow of the streams has already been appropriated by means of such irrigation works as are within the power of individuals, corporations or societies to carry out. But the more formidable engineering works that are necessary to effect storage are outside the possible limits of private enterprise, and fall within the province of Government to execute. President Roosevelt in his first message to Congress, 1901, admits this in the following words: "Great storage works are necessary to equalise the flow of streams and to save the flood waters. Their construction has been conclusively shown to be an undertaking too vast for private effort. . . . It is as right for the national Government to make the streams and rivers of the arid region useful by engineering works for water storage as to make useful the rivers and harbours of the humid region by engineering works of another kind."

The agricultural development of South Africa depends also to a great extent upon the storage of water in reservoirs.

The essential feature of such storage works as those contemplated in India and the United States will be, in most cases, a high dam designed after the type of dams already built for similar purposes, of which examples will be given in the next chapter.

Obviously the first condition that should be satisfied by any storage project is that there shall be a sufficient volume of flow off the catchment above the dam to fill the reservoir to the height necessary to provide adequate storage for the year's requirements in any year of which the rainfall is not exceptionally bad. The site of the reservoir must therefore be at a suitable distance below the actual sources of the river system to which it belongs. If the dam is to be a high one, it must have sound rock for its foundation. Gorges, at the outlet of a mountain valley, from which the hill-slopes above recede widely so as to enclose an expansive area, are the most favourable sites for dams. The height of the dam will be determined by the quantity that the reservoir is to be made to hold and by the configuration of the basin formed above it. A basin or valley with a gradually sloping bed will require a less height of dam to effect the storage of a given quantity than will be necessary if the slope of the bed is more rapid. But a deep reservoir has this advantage over a shallow one, that a less proportion of water is lost by evaporation.

It was remarked above that the scientific boundaries of tracts of country, hydrographically considered, are the water-sheds between their catchments. This scientific division has been, in some cases, upset by irrigation engineers themselves refusing to be bound by it. There are instances of the water supply of one catchment being diverted into a neighbouring catchment by carrying it round or through the water-shed ridge. This has been done on the Rocky Mountains in Colorado. On the west side the supply exceeds the demand,

but on the east there is less than enough. Consequently the supply of the west has been carried in channels or tunnels to the east side of the water-shed, and made to do duty there. "The Sky Line ditch," to cite a particular instance, carries water in a channel cut in the rock round the mountain tops at an altitude of 10,000 feet, and diverts it from one of the upper tributaries of the Laramie river to Cache-la-Poudre valley, Colorado.

There is a remarkable instance of the diversion of the water of one catchment into another to be found in India. The district of Madura, in Southern India, has frequently suffered from famine, lying as it does on the eastern side of the Ghâts, where the rainfall is scanty and very uncertain. On the western side of the Ghâts, however, the rainfall, which is copious and unfailing, under natural conditions finds its way down the channel of the Periyar river and discharges itself uselessly into the sea. At one point in its course the Periyar river is separated by a few miles only from one of the tributaries of the Vaigai, the river of the eastern catchment on which Madura relies for its irrigation. At this point a channel of connection has been made between the Periyar and Vaigai rivers, and, in addition, a reservoir has been formed on the Periyar river for storing the rainfall of its catchment. The Vaigai is thus fed by the rain which falls on the other side of the water-shed separating it from the Periyar catchment. The connection between the two consists of a tunnel cut in the rock through the intervening hills, 5,704 feet in length. The reservoir of the Periyar river is formed by a dam, 1,241 feet in length and 155 feet in height from river bed to crest, built across a very narrow gorge. The reservoir holds 13,300,000,000 cubic feet of water, of which the upper 6,815,000,000 only are available for irrigation. The catchment above the dam has an area of about 300 square miles, and the rainfall is said to be more than 120 inches in the year. The reservoir has a water-spread of about 12 square miles. But it is not only the amount stored that is available for irrigation on

the Vaigai, but the discharge of the Periyar river as well; so that altogether a total volume of about 30,000,000,000 cubic feet is diverted during the year from one catchment to the other.

A bold project has been recently sanctioned in India, which also depends for its working on the use of the water of one catchment for irrigation in another. A reservoir does not form a feature in this project, as the rivers concerned are snow-fed. The rivers are the Jhelum on the west, the Chenab in the middle, and the Ravi on the east. There is land requiring irrigation between the Jhelum and the Chenab, also between the Chenab and the Ravi, and again on the east of the Ravi. The Chenab and the Ravi have no water to spare, as existing irrigation has claims to the whole supply. But there is water to spare in the Jhelum. So it has been decided to carry the surplus of the Jhelum across to the Chenab, and thus release a corresponding volume of the Chenab discharge for the irrigation of the tracts to the east of it. This discharge will be carried in a canal, which will irrigate the land alongside it between the Chenab and Ravi rivers, and then pass under the Ravi river by a great syphon to irrigate the lands to the east of the Ravi. Over £5,000,000 has already been sanctioned for the carrying out of this project. An interesting detail of it is the proposed syphon, 1,400 feet long, designed to pass a discharge of 6,500 cubic feet a second under a river having a flood discharge of about 200,000 cubic feet a second. As the foundations go down to about 27 feet below spring water level, the construction of the work will be one of exceptional difficulty.

Further particulars concerning some of the more important reservoirs and dams already constructed or projected will be given in the next chapter. But before leaving the subject of supply, mention must be made of one of the earliest systems of irrigation in India—the system of surface tanks. Thousands of these tanks in Madras provide irrigation for millions of acres of rice crops. They vary in size from a few acres to nine or ten

square miles of water surface. They are usually formed by earthen embankments thrown across small local drainages, often of only two or three square miles in area, or by a series of such embankments thrown across the valleys leading from larger catchments. The Madras tanks depend mainly on local rainfall, but are sometimes fed from rivers or streams by means of channels taking off above weirs constructed in the beds of the rivers.

The relative importance of the tank system in India, as compared with other systems of supply, may be gathered from the following figures :—

Area in British India irrigated from wells .	13,000,000	acres.
,, ,, ,, ,, canals .	17,000,000	,,
,, ,, ,, ,, tanks .	8,000,000	,,
,, ,, ,, in various ways	6,000,000	,,
Total area in British India irrigated .	44,000,000	,,

Tanks are the primitive forms from which the more modern and imposing reservoir has been evolved; but as the early form is so well adapted to certain conditions, it has survived, with but little modification, in those situations where the conditions favourable to development to the higher type do not exist.

In the United States there is a class of reservoirs which in some respects resemble the Indian tanks. They are formed in suitable places among the foothills or out on the plains where convenient depressions exist in the neighbourhood of irrigable farms. They are filled by large canals, taking off from a river, with the surplus discharge which may not be needed for direct irrigation, either during the flood or other seasons. From these river-fed reservoirs the water is carried in canals to the fields to be irrigated.

CHAPTER V.

DAMS AND RESERVOIRS.

THE further agricultural development of India, Egypt, the Western States of America, Western Canada, South Africa, Spain and other arid countries depends largely on irrigation. In the countries named, Canada only excepted, almost all future extensions of irrigation will involve the construction of storage works. The subject of reservoirs has, therefore, an increasing importance to the present-day student of irrigation.

The climatic conditions which create a demand for and favour the formation of storage reservoirs are a deficient or uncertain rainfall during the period of the growth of crops, and at other seasons a constant and heavy rainfall over the area from which the crops obtain their water supply. Such are the conditions which are usually associated with perennial irrigation, and it is this which explains the almost universal need of storage works in countries which have dry and rainy seasons. The more valuable crops, as, for instance, sugar-cane and cotton, are those which require watering during the spring or summer months, when the natural water supply is often at its lowest.

Before looking for a reservoir site, it is necessary to ascertain, from such rainfall statistics as may exist, whether a reservoir, if made, will fill with sufficient regularity to justify confidence being placed in it as a reliable insurance against deficiency of supply. If the rainfall statistics give encouragement enough, the catchment area should be examined with a view to selecting a favourable site for a reservoir. The nearer the reservoir is to the land to be irrigated the better, for several reasons. Not only will the loss of water in transit between reservoir and crop

from evaporation and absorption be less, and the accommodation of the supply to the demand be easier, but the extent of the collecting area will be greater than it would be if the reservoir were removed to a site higher up the catchment basin. But, as a rule, the configuration of the ground determines the best site for the reservoir, and the selection of the site is not so much a matter of choice as a recognition of Nature's decision in the matter.

When the situation of the future reservoir is known, the question of its annual replenishment can be studied. The period and amount of rainfall, the proportion of flow-off to total rainfall, and the area of the catchment, are the necessary data required for the determination of the question. The catchment area can generally be measured with sufficient accuracy on existing maps; otherwise a survey will have to be undertaken to ascertain the lie of the watershed lines and the area enclosed by them. The rainfall statistics are generally imperfect, and the proportion of flow-off a most difficult thing to estimate. That the rainfall statistics are usually imperfect is not surprising, considering what is held to constitute completeness of the rainfall record. It is not enough to have the rainfall readings of one or two stations in the catchment. The observations must be made in at least as many sites in the catchment as will give values representative of all the local variations in the annual amount of the rainfall. Moreover, to include all the cyclical changes, the statistics should embrace the observations of thirty-five years, as less than this may not include years of extreme conditions. If, however, the records do not exist, there is no choice but to make the best of imperfect data, and to allow a wide margin of safety.

But, even though the rainfall statistics may be as complete as could be desired and the catchment area accurately known, there will still remain much uncertainty as to the quantity that will reach the impounding basin. Only a proportion of the rain that falls on the catchment area flows off it. The rest

is evaporated or absorbed. The amount that is evaporated varies with the temperature and the hygrometric condition of the air. The amount absorbed varies with the nature of the soil and its degree of dryness or saturation at the time of rainfall, and depends on the surface slope and configuration of the collecting basin, and on the presence or absence of trees or smaller vegetable growth. The proportion of flow-off is also affected by the intensity of the rainfall. In Chapter IV. of Buckley's "The Irrigation Works of India," and in Strange's "Indian Storage Reservoirs," valuable statistics of "flow-off" from different catchments in India are collected, and the conclusions to be drawn from them discussed. It appears that the conditions of rainfall and catchment may vary to such an extent that the proportion of flow-off to total rainfall may correspondingly vary from nothing to 98 per cent. It would seem, then, almost a waste of labour to attempt to calculate the quantity of water that will reach the reservoir with factors of which one is so variable as the figure representing the proportion of flow-off. And so perhaps it would be in the absence of a somewhat intimate knowledge of the nature of the catchment area and of its rainfall, or without the experience necessary to make correct deductions from such knowledge. Consequently it is better, whenever it is possible, to base the estimate of the quantity of flow-off on the discharges of the streams which actually drain the area, if, by any means, they can be even approximately determined.

Still, the subject of calculating quantities of flow-off by means of rainfall and catchment figures cannot be dismissed by throwing discredit on the data commonly available, as there may be no other method possible of arriving at any conclusion concerning the prospects of filling the reservoir and as to the allowance of escape waterway that must be provided to pass off any excess reaching the reservoir when it is full. The flow-off and its relation to the rainfall have been carefully studied in the case of many reservoirs in India, and, in the hands of

anyone competent to make proper use of it, the record of the observations made forms a useful guide for estimating the flow-off from catchments which are known to have similar characteristics to any of those to which the record applies.

Perhaps the conditions which most affect the proportion of the flow-off are the state of the catchment at the time of rainfall and the intensity of the rainfall. Mr. Strange gives the following figures as a rough approximation of what may be expected from an ordinary drainage area:—

Rainfall in Inches in Twenty-four Hours.	Condition of the Catchment. Percentage of Flow-off to Rainfall.		
	Dry.	Damp.	Wet.
0·25	Nil.	Nil.	12
0·50	Nil.	10	14
1·00	5	14	20
2·00	10	25	34
3·00	20	40	55
4·00 and over.	30 to 40	50 to 60	70 to 80

In India it has been found that, in tracts where the rainfall in the five monsoon months is about 40 inches, the percentage of flow-off has an average monthly variation represented approximately by the following figures:—

	Assumed Rainfall.	Flow off.
June . .	6 inches	— 5 per cent. of rainfall.
July . .	11 „	— 15 „ „
August . .	11 „	— 35 „ „
September .	8 „	— 50 „ „
October .	4 „	— 30 „ „

With a monsoon rainfall of less than 40 inches the percentage of flow-off would be less. These figures, however, must only be taken as relatively correct, and as indicating in a rough way the manner in which the percentage of flow-off varies with the saturation of the soil and the intensity of the rainfall.

The result of the calculations of flow-off will serve to show (if the data used have been correct) whether the catchment will furnish the quantity of water required to make the reservoir a success as a main or supplementary source of supply to an irrigation system. To be a success, the supply must not fail in years of deficient rainfall; though some hold that it is not necessary to insist that it must be equal to the demand in years of exceptionally scanty rainfall, which come but seldom. Whether shortcomings in such years may be deliberately contemplated as admissible in the preparation of a reservoir project, must depend on the circumstances of the particular case. But a reservoir which fills in years of ordinary rainfall when its assistance may not be much wanted, and fails to fill in years of deficient rainfall when there is urgent need of its help, does not justify its existence and the cost of its construction.

Assuming, however, that the study of the rainfall and catchment conditions have led to the conclusion that the replenishment of the reservoir is assured, there remains another matter to investigate. It is most important to determine the maximum discharge that the by-wash or escape of the reservoir will have to pass. An under-estimate of what this may be might be followed by disastrous results. The fate of the Nadrai aqueduct in India conveys an impressive lesson. This aqueduct carried the Lower Ganges Canal over the Kali Nadi, a channel which drains an area of 2,377 square miles. The waterway allowed under the aqueduct for the discharge of the Kali Nadi was calculated on the basis of the then highest recorded flood of 23,000 cubic feet a second, equivalent to 9 cubic feet a second per square mile of drained area, or 0·33 inches in depth over the entire catchment in twenty-four hours. In July, 1885, a flood of 130,000 cubic feet a second—six times as great as the maximum previously recorded—caused a rise at the aqueduct of 20 feet above the highest water mark of previous years, and destroyed the work. The aqueduct has

since been rebuilt and a sufficient waterway provided for the safe passage of 140,000 cubic feet a second, which is, since the accident, the accepted figure for the maximum discharge of the Kali Nadi.

To guard against such an unwelcome surprise as was experienced in the case of the Nadrai aqueduct, it is necessary to ascertain the maximum discharge from the catchment in periods of heaviest rainfall and greatest flow-off. So it is desirable to have a record, not only of the daily rainfall, but also of the heaviest rainfall that occurs in shorter periods than a day, even sometimes in fractions of an hour. Unfortunately it is not likely that this information will be obtainable, at any rate during the period of study of any new reservoir project. So, again, it will be better, if possible, to calculate with whatever figures may be obtainable from observations on the streams by which the flow-off reaches the reservoir. There may be a record of discharges kept; or, if there is no such record, discharges may be taken expressly for the purpose of the reservoir study. The residents of the locality may, possibly, be able to point out the highest marks reached at different places along the course of the streams by the greatest flood known to them. From these marks the surface slope of the flood can be ascertained, and with the gradient thus determined, and with cross-sections of the waterway taken opposite the marks, the flood discharges can be calculated. This method of estimating the maximum discharge which flows off a catchment will give more reliable results than calculations based on rainfall statistics and an assumed value for the proportion of flow-off. But if the former method is not practicable, the latter must be followed *faute de mieux*. In the calculation of the maximum flow-off, the time occupied, or the rate of flow, is an important factor. In steep and barren catchments the rate is rapid, and the total flow-off arrives in the reservoir in a shorter time than it does from catchments of gentle slope or wooded surface. Also from small catchments the flow-off is

rapid relatively to that of large catchments. As the circumstances of every case differ so widely, it is impossible to lay down rules for calculating what discharging capacity should be given to the reservoir escape. The peculiar circumstances of each case must be studied and the allowance determined to the best of one's judgment. Formulas there are which are used in India to work out what discharge per square mile of drainage area the reservoir escape should provide for, but the correctness of the results obtained depends altogether on the discretion with which the formula is used. The co-efficient, which is the controlling factor of the formula, varies from 150 to 1,000, and even more. The use of any of the formulas does not avoid the necessity of a right judgment of the special conditions affecting the particular case under consideration. With this warning the formulas most commonly used are given below. In both of them

D = discharge in cubic feet per second,
M = area of catchment in square miles,
C is a co-efficient.

(1) Dickens' formula: $D = C \sqrt[4]{M^3}$

(2) Ryves' formula: $D = C \sqrt[3]{M^2}$

In Madras, Ryves' formula is generally used with the following values for C :—

Within 15 miles of the coast — 450,
Between 15 and 100 miles from the coast — 563.
For limited areas near the hills — 675.

In the Bombay Presidency the waste weirs of tanks and reservoirs are designed to discharge from 212 to 967 cubic feet per second per square mile of catchment, the allowance varying with the amount of average annual rainfall, with the area of the catchment, and with the slope of the river above the reservoir. In other parts of India the discharge which the reservoir escape is designed to pass may vary between 150 and 600 cubic feet a second per square mile of hill areas, and between 25 and 160 from areas in the plains. But there is a case of a tank in

India, fed by a rocky catchment of small area, in which the discharging capacity of the waste weir is as much as 1,936 cubic feet per square mile; and another as much as 3,514 cubic feet. The latter, if not also the former, is probably in excess of requirements.

The storage capacity of the reservoir may be limited by the physical features of the site, the amount of flow-off from the catchment that can be relied upon, or by the requirements of the land to be irrigated. As a rule the demand is greater than the maximum supply possible, and it is the volume of the flow-off that determines what capacity should be given to the reservoir. There are limits to the height to which it is safe or practicable to build dams to store water, and the configuration of the ground may be such that no reservoir site can be found which will contain the required volume of storage without constructing a dam of a height exceeding the maximum permissible. The capacity of the Assuan reservoir in Egypt was limited for exceptional reasons. The temples on the island of Philæ had worshippers whose vigorous protests against the submersion of buildings which some of them had never seen, resulted in the dam being built to a height 26 feet lower than was originally intended. The capacity of the reservoir was thus reduced from 2,500,000,000 cubic metres to 1,000,000,000.

The gross capacity of a reservoir is calculated from the areas bounded by the contours between the high water level of the reservoir and the reservoir bed. Its "available capacity," or the quantity that is supplied by the reservoir through its outlet, is the volume stored between the high water level and the sill of the outlet, less the loss due to evaporation and absorption in the reservoir after it has been filled and replenishment ceases.

The deduction to be made on account of evaporation depends upon the length of time the water is stored after the final replenishment, and on the temperature and hygrometric state of the air for that period. Observation alone can determine exactly what the deduction should be. There is also a loss

from leakage and absorption depending on the nature of the bed of the reservoir. It may be taken roughly as equal, in the year, to half that due to evaporation. The loss due to evaporation in a year, measured in vertical height, may vary from 3 to 10 feet, according to the climatic conditions.

The dam, which is the principal feature of a reservoir project, may be made of earth or of masonry, or of a combination of both. There are dams of a type peculiar to America known as "rock-fill" and "loose rock" dams. They are formed of a mass of rubble with a water-tight facing, which may be of planks, of asphalt or Portland cement concrete, of masonry, of steel plates, or of earth. Another type peculiar to America is a dam, either of earth or loose stone, with a central core of steel plates forming a water-tight diaphragm embedded in the mass of the dam.

Masonry dams may be classified as—

(*a*) Solid submergible dams, over the crest of which the discharge passes;

(*b*) Solid insubmergible dams, with waste weirs to discharge excess water, and outlets for the delivery of the stored water;

(*c*) Insubmergible dams, pierced with numerous sluices, through which the discharge is passed.

Earthen dams must always be insubmergible, and be provided with waste weirs and outlets. They may be divided into three classes, namely,—

(*d*) Dams with masonry core walls;

(*e*) Dams with central puddle core;

(*f*) Dams entirely of earth without core walls.

The question as to which class of dam is the most suitable for any particular site depends to a great extent on the nature of the foundation. A high masonry dam must have sound rock for its foundation. This is a *sine quâ non.* An earthen dam may be built on sandy or gravelly clay, fine sand or loam, and also on rock if proper precautions are taken to prevent creep of water between the bed of the dam and the rock surface.

Earthen dams can be safely built up to 75 feet in height, though French engineers fix the safety limit at 60 feet. No doubt 60 feet is a safer limit than any greater height, but there are earthen dams in India, exceeding 75 feet in height, which have now been tested by many years of useful work. There are in existence also earthen dams of 80 and 100 feet in height, and one of even 125 feet. Mr. Strange considers that embankments above 75 feet in height should be reinforced by adding dry stone toes to the slopes, and that, with this addition, dams might be safely constructed up to 125 feet in height. He admits, however, that when a height of 60 feet is exceeded particular care must be taken both with the design and with the construction.

The choice between earth and masonry for the dam construction is affected also by economical considerations, and the facilities for transporting materials to the site of the work.

As earthen dams are doubtless of earlier origin than masonry dams, they will be considered first.

The design and construction of earthen dams has been treated fully by Mr. W. L. Strange in his practical treatise on "Indian Storage Reservoirs with Earthen Dams" (1904), from which much of what follows relating to them is borrowed.

The design of an earthen dam includes the dam proper, the waste weir, and the delivery outlet. The safest arrangement is when each of these three works are separate one from the other, the waste weir being on one side of the dam and the outlet on the opposite side. But for the sake of economy, or other reasons, they are often combined in one work. The more common arrangement is to combine the dam and outlet in one work, and to separate the waste weir. If the three works are separate, and there is no outlet passing through the dam, it is probably best to construct the dam entirely of earth of the same character throughout, the soil selected being of a description that is impervious and stable under the action of water. The cross section of such a dam of ordinary good soil, if from

50 to 75 feet in height, should have the following dimensions:— The crest of the dam should be 6 or 7 feet above the high water level of the reservoir; the crest width should be 10 feet; the up-stream slope on the reservoir side should have 3 of base to 1 of rise, and the down-stream slope 2 to 1. If the dam is 15 feet high or under, the crest of the dam may be 4 to 5 feet above high water level, the top width 6 feet, up-stream slope 2 to 1, and down-stream $1\frac{1}{2}$ to 1. For dams of heights between 15 feet and 50 feet the dimensions may be intermediate between the foregoing.

It will be necessary to protect the up-stream slope between low-water level and high-water level with a skin of dry rubble revetment, or of some other suitable material, to resist the erosive action of the waves of the reservoir; and the down-stream slope also must be so clothed as not to be guttered by rainfall.

The reinforcement of the slopes of earthen dams of more than 75 feet height by the addition of dry stone toes is desirable to give security against sliding. The down-stream stone toe is also useful in providing for the drainage of the heart of the dam without injury to the down-stream face, and is, on this account, preferable to the solid masonry retaining wall which has been added to some dams as a support to the down-stream slope. The Maladevi Tank dam in Bombay has been designed as an earthen dam with dry stone toes. At its highest point it is subjected to a water pressure of 98 feet. Its up-stream and down-stream slopes are 3 to 1 and 2 to 1 respectively, but these slopes change above high water level. The up-stream face above high-water level is protected by a crest wall of masonry with a batter of $\frac{1}{2}$ to 1, the down-stream slope changing to $1\frac{1}{2}$ to 1. The up-stream wall of masonry protects the crest from wave-wash, acting as a breaker. It also prevents burrowing animals from injuring the dam.

In the construction of earthen dams, particular attention must be given to the foundations. Not only must precautions be taken to prevent creep of water between the natural ground

and the artificial earthwork of the dam, but provision must be made for intercepting any percolation water that may travel through the subsoil, or for leading it harmlessly away. Also, to prevent the dam itself becoming saturated and consequently slipping or subsiding, it is necessary either to guard against the water entering the dam, or to provide means of getting rid of it if it does enter. Thorough drainage of the earthwork and of its foundations is, therefore, the condition essential to security. To the endeavour to exclude the water from the dam, cut off the creep at or below foundation level, and provide drainage for the dam and its foundations, the different types of earthen dams are due.

The first condition for the adoption of an earthen dam in a storage project is that the soil of the foundations and that for the construction of the dam itself must be suitable, the one to withstand the weight of the dam, and the other to resist the passage of water and any tendency to saturation.

Borings into the foundation, or trial pits, will reveal the nature of the subsoil and furnish the information necessary for determining the measures to adopt in each case. If the subsoil is porous (and most subsoils are more or less), or if it is of rock with porous seams, the usual course is to make a puddle trench under the centre of the dam to offer a water-tight obstacle to the movement of the water, so that all down stream of it may be kept dry. The bottom width of this curtain should not be less than 6 feet for small dams, nor less than 10 feet for high dams. The usual rule is to make the base width equal to one-quarter of the full supply depth of the reservoir at any given point. The depth of the puddle trench will depend upon the porosity of the soil and the head of water in the reservoir, and may vary from half the depth to the whole depth of the full supply storage in the reservoir, or more. The trench must be carried down until it enters for 2 feet at least into good clayey soil extending downwards. Or, if rock is met with before reaching these depths, the trench should be carried at least 1 foot down into the rock to form a good joint with it.

If sandy and highly porous layers exist to a great depth, it may be necessary to condemn the site and give up the project.

To cut off the creep between the natural ground and the artificial bank above it, the puddle filling of the trench should be continued upwards past the plane of junction for a foot or more, so as to make a bond with the earthwork of the dam. The foundation of the dam should also be benched to present surfaces for the dam to rest on slightly inclined towards the centre of the dam. Along the bottom angles of this benching which are up stream of the main puddle trench, small puddle trenches should be formed parallel to the main trench, and along the angles of the down-stream benching trenches should be made and filled with porous material to serve as foundation drains. In the Maladevi Tank dam, where it rests upon rock, concrete walls, sunk in the rock surface, take the place of the puddle curtain barrier.

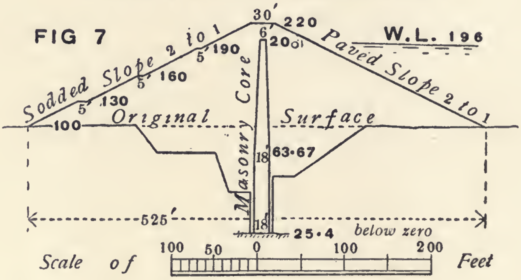
But, if the material of the dam is not absolutely water-tight, water will find its way through the mass of the dam to the down-stream face, possibly to a dangerous extent. To provide against this, the puddle trench has been sometimes developed into the puddle core by carrying up the puddle as a thin wall, in continuation of the puddle in the foundation trench, from the bottom of the dam to above high water level. By this means the penetration of water into the mass of the dam is confined to the half of it up stream of the puddle wall, and the stability of the down-stream half is not affected by any soakage. Regarding the dimensions to be given to puddle walls opinions differ, but Rankine's rule is that the thickness at the base should be about one-third of the height, and the thickness at the top two-thirds or one-half that of the base.

The objection to a puddle core is that it is liable to rupture from unequal settlement of the earthwork of the dam, and it then ceases to be water-tight. For this reason, masonry core walls are to be preferred, though, generally speaking, their cost would be considerably greater. But a masonry core wall

requires solid and sound rock for its foundation, and therefore cannot take the place of a puddle core unless this condition is fulfilled. If the waste weir or outlet, or both, are combined with the dam in one work, the masonry core wall adds considerably to the security, as it enables a perfectly sound bond to be made between the dam and its associated works. This is important, as an outlet, for instance, passing through an earth dam without a masonry core wall, is always a source of

CROTON DAM

EARTHEN LENGTH



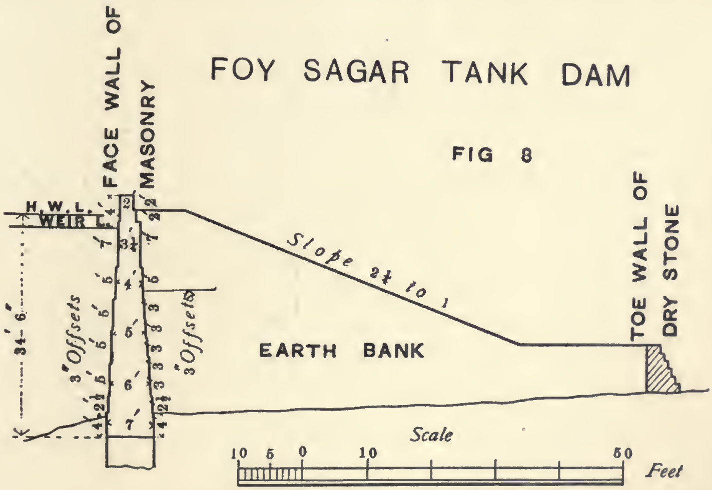
weakness, offering a line for leakage if there should have been anything defective either in design or execution.

Whether the core be of puddle or masonry, it must be continued outwards to both flanks up to high water level, the changes of level in the foundation bed of the core at the flanks being effected by vertical rises. Great care must be taken to form a good bond between the dam and its natural abutments lest a leak should form between the two. Opinions differ also as to the dimensions that should be given to masonry cores. The earthen length of the New Croton dam, New York, is considered to be of good design (Fig. 7[1]). It has a masonry core which is carried down to a depth of 125 feet below the original surface; for 89 feet from its foundation level it has a width of 18 feet, and thence it gradually decreases to a top width of

[1] The earthen length after partial construction was altered to a solid masonry band.

6 feet at a level 14 feet below the crest. This dam has a height of 120 feet above the original ground surface. It abuts on to another length of dam in masonry.

The position of the water-tight component of a dam in the centre of the embankment is theoretically an unfavourable one. The water enters the up-stream half of the dam and reaches the core wall. It is thus the impermeable core wall, backed up by the down-stream half of the dam, which does all the retaining work. The up-stream half is only useful in preventing the wall



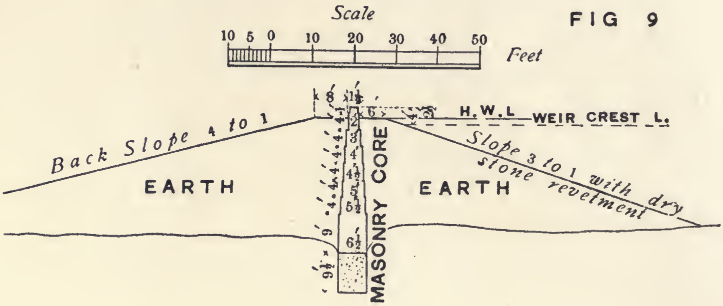
from falling inwards towards the reservoir when the latter is empty. So dams of a section, such as that of the Foy-Sagar Tank (Fig. 8), would appear to answer all the purposes of a full-section earth dam, provided the wall is strong enough to hold up its backing when the reservoir is empty. The dimensions of the face wall of the Foy-Sagar Tank dam are certainly remarkably light, and are even less than those of the core wall of the Kair Tank dam (Fig. 9) which has a support of earth on both sides.

In consequence of the theoretical objection to the situation of the impermeable diaphragm in the centre of the mass, a

puddle surface has sometimes been given to the reservoir face of the dam to prevent the water from entering the bank at all. But there is a practical drawback to this arrangement which has caused its rejection: the puddle is liable to slide and crack when the water level in the reservoir is low or the embankment settles, and so to be no longer water-tight. The puddle core in the centre of the dam, on the other hand, is protected, by reason of its position, from the effects of the weather, and has no tendency to slide or crack, so that it is more likely to remain water-tight. But with a masonry core wall this argument does not apply, and the up-stream half of the dam, as has been

KAIR TANK DAM

FIG 9



stated, only serves to support the wall when the reservoir is empty. As a masonry core wall cannot be built except on rock foundations such as would be suitable for a masonry dam, it would be a matter for consideration whether, instead of an earth dam with a masonry core or face, it would not be better to substitute a masonry dam.

There seems to be a growing tendency to prefer one of the two extremes, either an earthen embankment of uniform section and homogeneous material without any core wall, or a dam wholly of masonry. Between these two extremes lie all the composite varieties of dams. It is possible that one or other of the varieties may be found more suited to the special

conditions of a particular site than the all-earth or all-masonry dam would be.

Dams of the American type form a class by themselves. The dam with a central water-tight diaphragm of steel plates, however, belongs to the class of dams with masonry or puddle cores, as its principle of action is the same. It differs only as regards the material of which the dam is made in those cases in which dry rubble is substituted for earth to form the mass of the dam on either side of the core. The steel plate is embedded in a concrete base forming a junction with the bed-rock. In such a dam the principle is recognised that the core alone stops the passage of water, and the material on either side of it merely acts as a support to enable it to resist the pressure. Instances of this class of dam are to be found in Southern California.

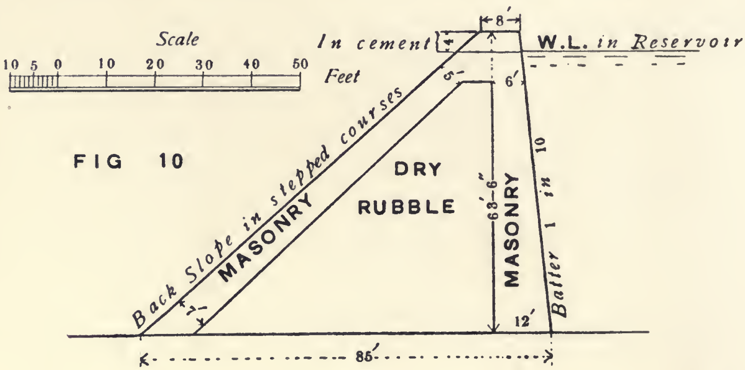
"Loose-rock" dams are simply dams made of dry rubble with an impervious up-stream face of tarred planking or earth. The safe section for this class of dam is not much less than that of an earthen dam: the upper and lower slopes, however, can be made steeper than those of an earthen dam; but 2 to 1 for the upper slope and 1 to 1 for the lower is as steep as they should be made. A facing of earth, supported by loose rubble below water, is not a good disposition of material. Wood also, being perishable, is not a good material for use in a permanent structure. So this type of dam is not in favour, nor is it likely to be.

The "rock-fill" dam is made of a mass of loose rubble with a front and back wall of masonry forming steep sloping faces. On the upper face there is sometimes added a covering of two thicknesses of planking with tarred paper between, the joints of the outer planks being caulked and the whole face painted. The "Walnut Grove" dam, built in this way, had a greatest height of 110 feet. It was topped and destroyed by a flood in 1890, the waste weir proving insufficient for its purpose. The dam of the Castlewood reservoir in Colorado,

another of this type, still exists as the only specimen of its class. Its section is given in Fig. 10. This kind of dam may be classed with the composite masonry and earth dams of the Foy-Sagar variety (Fig. 8), dry rubble taking the place of the earth backing and acting as a support to the face wall in the same way.

Such dams as "loose-stone" and "rock-fill" are of an inferior class to the all-masonry dam. The masonry dam, founded on sound rock, has fewer weak points in its constitution than other forms, and for certain situations is the only

CASTLEWOOD RESERVOIR DAM



form that could stand. Nothing but a masonry dam, for instance, would have been possible for the Assuan dam on the Nile. Examples of the three classes of masonry dams—the submergible, the solid insubmergible, and the pierced insubmergible—are given in Figs. 11 to 22, 25, and 26. A selection has been made from among dams of recent construction, as embodying the ideas of modern engineering concerning the design of high masonry dams, so far as recent work affords examples. The main dimensions of these dams are shown on the figures, and they will therefore, as a rule, not be given in the text.

The variety in design of existing dams is great, but in the

high dams constructed during recent years there is a tendency to uniformity of design where the conditions are similar. This is no doubt the result of a general acceptance of the theory of stresses in dams, which mathematical investigators had, till quite lately, held to be sound. The soundness of the theory, on which the design of most modern dams has been based, has now been called in question and is being put to the test.

The forces acting on a dam are—(1) the pressure of the water in the reservoir exerted in a direction at right angles to the up-stream face and (2) the weight of the dam itself acting vertically.

In a masonry dam the conditions of stability, as commonly accepted, are three, namely,—

(1) The lines of pressure, both when the reservoir is full and when it is empty, must lie within the centre third of the cross-section;

(2) The pressures in the masonry or on the foundations must never exceed safe limits;

(3) The friction between the dam and its foundation bed, or between any two parts into which the dam may be divided, must be sufficient to prevent sliding.

Compliance with the first condition gives security against overturning. Until lately it was assumed that it also precluded the possibility of tensile stresses on the masonry. But the justification for this assumption is now questioned, and it is contended that, if the dam is treated as an elastic solid, it is necessary to take account of the elastic shear as well as the elastic compression. Mr. Atcherley holds that it is not sufficient to consider the stresses in horizontal sections, but the stresses in vertical sections also must be investigated, and it will then be found that tensions exist in the toe of the dam to an extent that cannot be disregarded. Sir Benjamin Baker,[1] after discussion of this question, and admitting that tension in masonry should be avoided as far as possible, has expressed

[1] Vol. CLXII. "Proceedings Inst. C.E.," pp. 120, 456.

his opinion that, "whatever theory mathematicians might evolve, engineers would not be relieved from the obligation to use no materials for dams which would not stand, say, fifty tons per square foot in compression and ten tons per square foot in tension without splintering." In existing dams the actual maximum pressures vary as a rule from six to fourteen tons per square foot.

In practice it is found that if the above conditions (1) and (2) are satisfied, so also is condition (3).

Masonry dams of great height were first built in Spain.

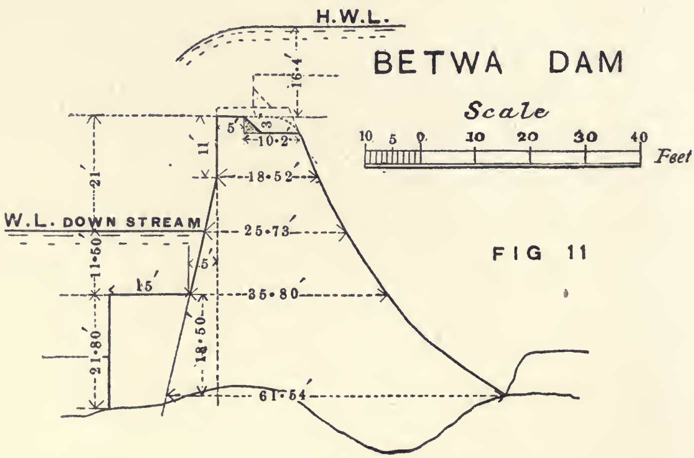


FIG 11

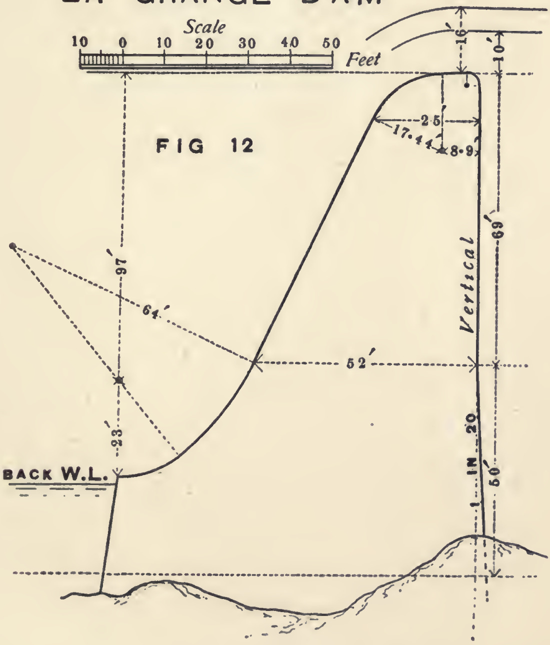
The Alicante dam, of 140 feet greatest height, was built between the years 1579 and 1594; but the Almanza dam, 68 feet high, was built at some unknown date long before. Nearly all the dams of Spain are built across mountain gorges on rock foundations.

The construction of the Furens dam in France, between the years 1862 and 1866, marks the next great advance in dam-building. The French engineers were the first to work out the scientific principles according to which dams should be designed, and to test their soundness by applying them to actual practice. The Furens dam, of a greatest height of

177 feet from foundation to crest, was the first dam to which these principles were applied. Its section is given in Fig. 17. It belongs to the insubmergible class.

Submergible dams, of which examples are given in Figs. 11 to 16, exhibit heavier profiles relatively to the height of the dam than those which are insubmergible. The submergible dams act as overflow weirs, and have to support the extra

LA GRANGE DAM



pressure due to the depth of water which flows over their crests, and also to resist the action of falling water on the down-stream side. Many, if not most, of the dams that belong to this class have subsidiary weirs associated with them. These weirs are built in the channel some distance down stream of the main dam with the object of holding up the water above them to form a pond or water-cushion on which the falling water may expend its force. The toe of the dam and the rock adjacent is thus

protected from scouring action. The Betwa dam, in India, (Fig. 11) has a solid platform of masonry for its down-stream toe, the upper surface of which is submerged 10 feet by the water ponded up by a subsidiary weir 18 feet in height. The shock of the falling water, moderated by the water-cushion, is thus borne by the solid projecting platform.

VYRNWY DAM

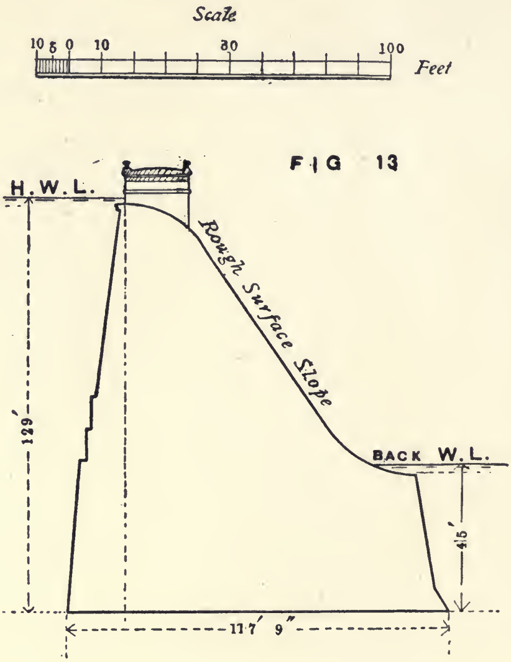


FIG 13

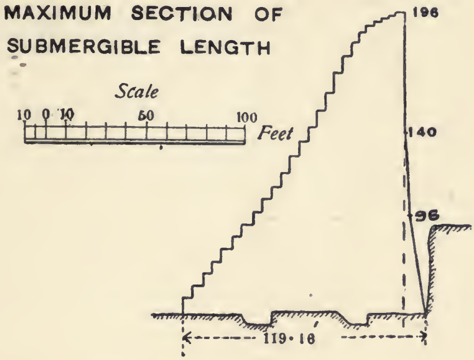
The Turlock, or La Grange dam, in California, (Fig. 12) has similarly a subsidiary weir, 20 feet high, situated 200 feet from the main dam. But it has no platform down stream, and its cross-section differs greatly from that of the Betwa Dam. The Turlock profile is, however, the more common form of the two, and is typical of a large number of existing submergible dams. The Turlock dam

is designed for a maximum depth of 16 feet of water flowing over its crest.

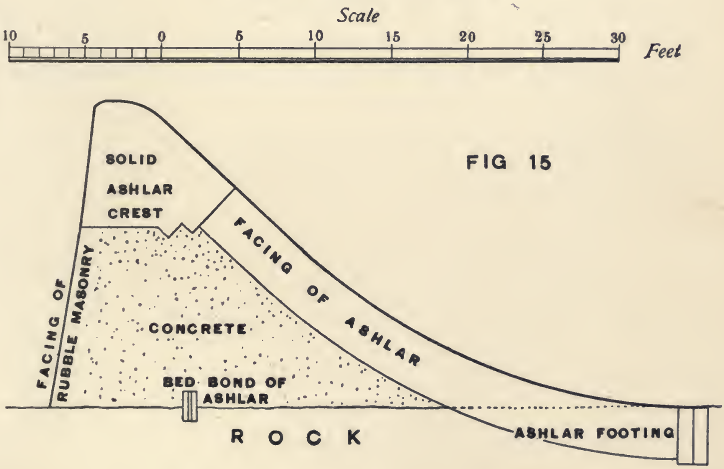
The cross-section of the Vyrnwy dam, in Wales, (Fig. 13)

CROTON DAM

FIG 14



HENARES WEIR

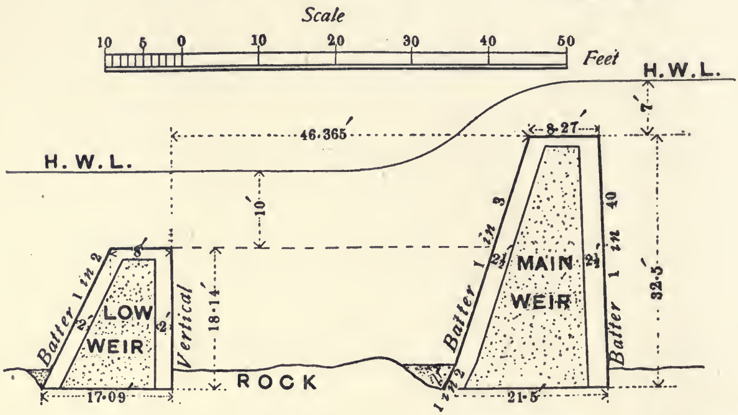


exhibits, though in not a very pronounced form, the ogee down-stream face. There is a cushion of 45 feet depth of water over its toe. The force of the falling water is, moreover, broken up during its descent over the down-stream face by the

roughness of the surface. Very large stones were available for the building of this dam, and were used in the down-stream face with the roughest possible exposed surfaces. In consequence of this arrangement the overflow, according to the description given by Dr. Deacon, reaches the pool below as "white spray" instead of as "solid water,"[1] the force of its fall being expended on the rough projecting surfaces of the down-stream face stones. This is as it should be. It is a mistake, sometimes made, to adopt the ogee curve for the down-stream face and to make the surface smooth. With such an arrangement the water glides evenly

NIRA DAM

FIG 16



over the crest and down the slope of the dam with a delusively harmless appearance. But the less resistance the water meets with during its descent, the greater will be its velocity and its power to work mischief on its arrival at the toe. The mistake was made in India on the Ganges canal when it was first constructed. The weirs were originally given ogee profiles, but they have since been converted into stepped weirs, or weirs with vertical drops, so as to prevent excessive horizontal velocity.

The Henares weir, in Spain, has the ogee form (Fig. 15). It should be classed, perhaps, as a river regulator rather than a

[1] Proceedings Inst.C.E., Vol. CLXII., p. 110.

submergible dam ; or it may be considered an intermediate type between the Indian anicut and a dam of the Turlock form. It is founded on rock which has sufficient strength to resist the action of the high velocity current acquired by the water in its unimpeded passage from above to below the weir.

The weir across the Nira river in India (Fig. 16) is a combination of two weirs, about 40 feet apart. The upper weir

FURENS DAM

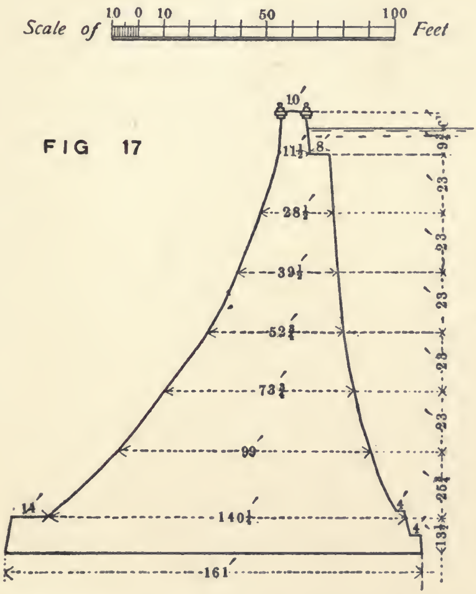


FIG 17

is 32½ feet high, the lower 18 feet, so that the water in the pool between the two is held up to a level which is 14½ feet below the crest of the upper weir. Both weirs are founded on rock. The objection to this arrangement is that boulders may get imprisoned between the two weirs and, under the action of the currents and eddies, may work deep pot-holes in the rock bed at the toe of the main weir. This is extremely likely to happen with weirs so close together as these. The vertical face of the

downstream weir would also prevent any loose stone, once caught between the weirs, from being carried away again by the current. This combination of weirs should be classed with the Henares Weir as intermediate between a river regulating weir and a submerged dam. It acts as both.

The highest submergible dam in existence is that of Mundaring, in Australia. It has a greatest height of 190 feet from

PERIYAR DAM

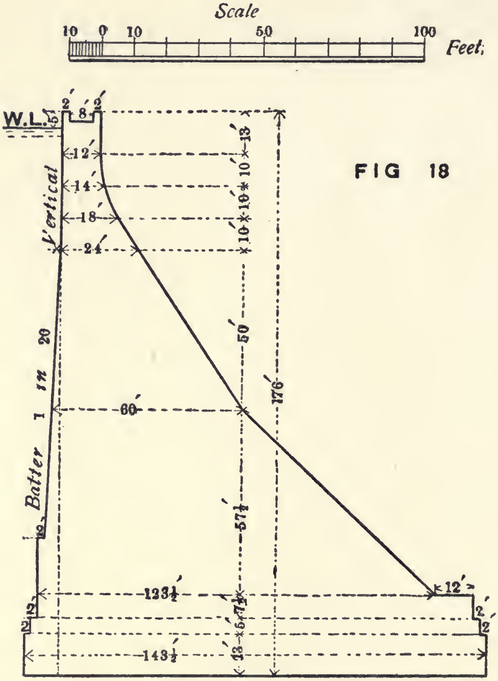


FIG 18

foundation to crest, which latter is 100 feet above the original surface of the ground. It is designed for a depth of overflow of 5 feet. In August, 1904, there was an overflow of 18 inches, the actual maximum up to that date.

Of the examples of solid insubmergible dams given in Figs. 17 to 22, the Furens dam has already been referred to.

The Periyar dam, in India, (Fig. 18) forms the most important

feature of the irrigation scheme to which reference was made in the preceding chapter as furnishing an illustration of the diversion of the water of one catchment for use in another. The dam is built in a narrow rocky gorge 269 feet wide at the bed and 1,241 feet wide at the parapet level of the dam. The reservoir came into operation in 1896.

MARIKANAVE DAM

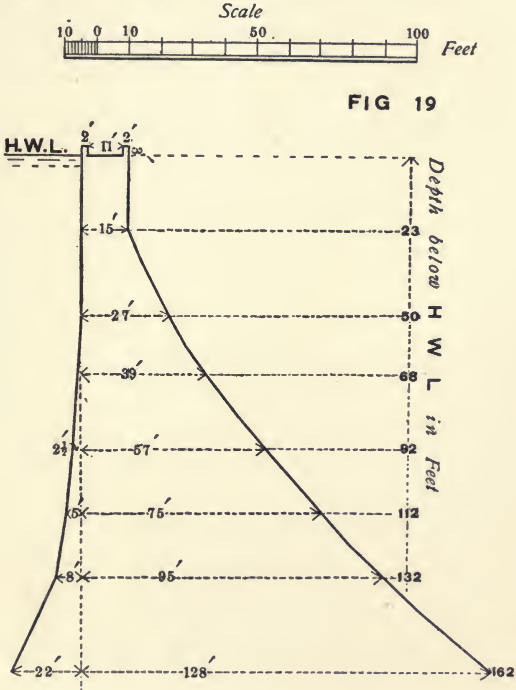


FIG 19

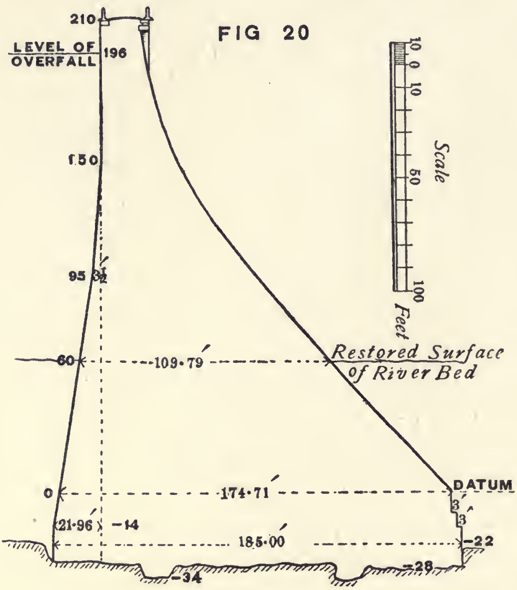
The Marikanave dam, in India, (Fig. 19) is also built in a gorge, which is 1,200 feet broad at the dam crest level. The reservoir formed by it is the largest in India, and has a gross capacity exceeding that of any other reservoir in the world, excepting only the Assuan reservoir on the Nile. Its water-spread is 34 square miles, and maximum capacity 40,000,000,000 cubic feet. The storage capacity of the reservoir is, however,

greatly in excess of the calculated annual replenishment, so that it is not expected to fill more than once in thirty years. It was for economical reasons that the dam was given the extra height which has provided the excess storage. [1]Sir Thomas Higham has explained how such a proceeding could result in economy. "The average annual rainfall is not more than 25 inches,

CROTON DAM

INSUBMERGIBLE LENGTH

FIG 20



and the inflow due to such a fall will probably not exceed 10,000,000,000 cubic feet. In some years it may be less, or even *nil.* It was originally proposed to provide a capacity of 20,000,000,000 cubic feet, which would about equal the inflow due to an annual rainfall of 30 inches; but there were records of cyclonic rainfalls, the run-off of which would not only fill a

[1] "Irrigation," Transactions American S.C.E., 1904.

tank of this capacity, but would also require an overflow capacity of 60,000 cubic feet a second. Such an escapage could only be provided by cutting a deep channel of adequate dimensions through hard rock, and, as a matter of arithmetic, it was found to be cheaper to increase the height of the dam, and to place the bed of the escape at a higher level."

The New Croton dam, which was substituted for the proposed Quaker Bridge dam, has been constructed to impound water for the supply of the city of New York. Like the Titicus dam, it is made up of three sections which furnish illustrations of the earth dam with masonry core (Fig. 7), of the submergible masonry dam (Fig. 14), which serves as the waste weir or overfall to the reservoir, and of the solid insubmergible masonry dam (Fig. 20). The insubmergible length has a height of 300 feet at the point where the foundations are lowest, a height which would have been considered extreme not many years ago.

The above-mentioned insubmergible masonry dams, chosen as typical examples, are all either built on straight alignments or on a curvilinear trace so flat as to be considered straight in calculating the dimensions of the dam. The Furens dam, for instance, has a curvature of 827 feet radius, but its profile was, nevertheless, designed as if for a straight dam. There are a few dams, closing narrow gorges, which depend for their stability on the fact that they are built to a curved plan which brings into play the principles of the arch. The outer ends of these dams abut on the rocky flanks of the gorge, to which the water pressure is transmitted. The transverse dimensions of the dam can, therefore, be reduced considerably, and it is no longer a necessary condition of stability that the line of pressure, when the reservoir is full, must lie within the centre third of the cross-section. But the weight of the dam itself must, nevertheless, be borne by the foundations, so that the condition that the pressure in the masonry or on the foundations must never exceed safe limits, must still be complied with. The following

statement gives details about four remarkable curved dams, three of which are in California :—

Name of Dam.	Country.	Maximum Height.	Radius of Curvature.	Length of Dam at Crest.	Top Width.	Bottom Width.	
		Feet.	Feet.	Feet.	Feet.	Feet.	
Zola . .	France .	123	158	205	19	42	See Fig. 21
Sweetwater.	California	90	222	380	12	46	
Bear Valley	"	64	300	450	3·2	20	See Fig. 22
Upper Otay	"	75	359	350	4	14	

Figures 21 and 22 give the cross-sections of the Zola and Bear Valley dams.

Reservoirs that are formed by solid dams holding up water to considerable heights are doomed to extinction by silt deposit, sooner or later according as the proportion of silt, that is carried in suspension by the streams that fill them, is great or small. The small scouring sluices, with which some of such dams are provided, are efficient in removing the deposit of silt only in cases where the reservoir is very narrow and has a very steep sloping bed. India, Algeria and Spain can furnish instances of reservoirs that have become extinct by the silting up of their basins. In Spain, the Val de Infierno dam,[1] 115 feet high, has been for many years a useless waterfall, the reservoir basin having silted up to the crest of the dam. The reservoir above the dam of Alicante, in Spain also, silts up to a depth of 40 to 50 feet against the dam in four years. The scouring sluice is then brought into operation, and the deposit removed by the escaping water. At least, this *should* be done every fourth year; but the intervals between two scouring operations is generally longer. In the case of the Alicante dam, the sluice acts well and the reservoir is kept clean, probably because the basin is narrow and steep. As the scouring sluice of the Alicante dam is typical of the sluices of both Spanish and Algerian dams, Sir

[1] "Irrigation du Midi de l'Espagne," by Aymard.

William Willcocks' description of such a sluice will be given. Figs. 23 and 24 are referred to in the following description: "The under-sluice at Khamîs (in Algeria) is on the Spanish principle. It is situated at the bottom in the line of the bed of the original stream. A Spanish under-sluice consists of an opening of from 1 to 3 metres in height, and from 1 to 2 metres

ZOLA DAM

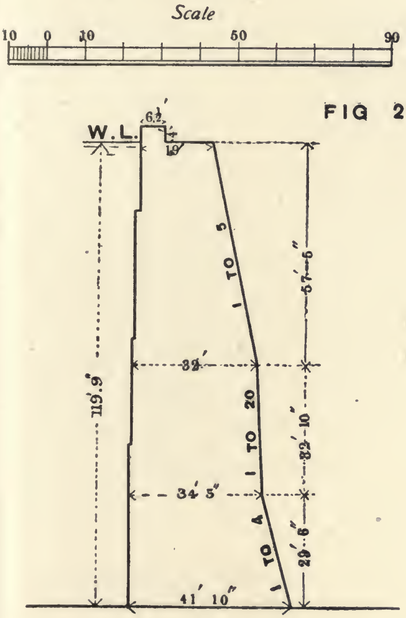


FIG 21

BEAR VALLEY DAM

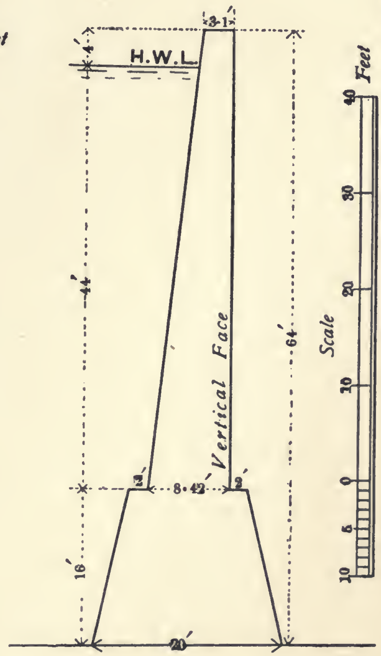


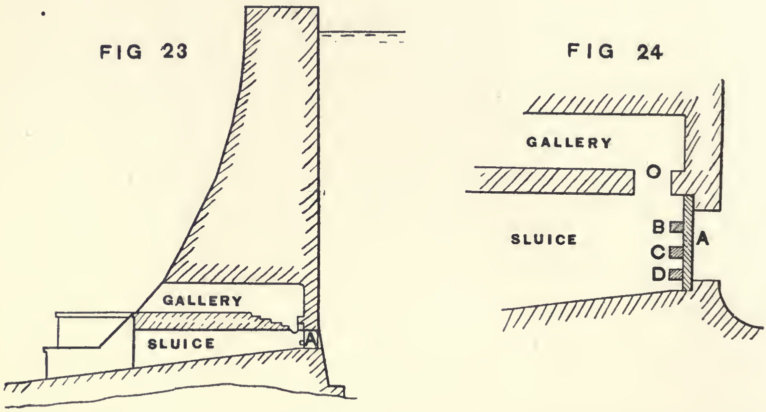
FIG 22

in width at the up-stream end; it increases gradually as it advances down-stream, and it is sometimes as much as 4 metres wide and 6 metres high. This opening is closed at the up-stream end by a wooden door, called a Spanish door, supported against horizontal timbers let into apertures in the two sides at the point A in the figures. Just above the under-sluice is a gallery. This gallery is about a metre wide and 2 metres high, and is closed on the up-stream side, and open on the

down-stream face to allow workmen to enter. It communicates with the under-sluice by an opening some 60 centimetres in diameter just down-stream of the gate A (Fig. 23).

The door is put in position in the under-sluice from the down-stream side when the reservoir is empty, and the three horizontal timbers B, C, D (Fig. 24) are let into slots in the jambs, and the whole door is well caulked. The water now rises in the reservoir, and as the deposits accumulate, they bury the door and gradually gain great consistency. It takes four years for

SPANISH UNDERSLUICES
FOR SCOURING



the deposit to become solid, though it is generally left ten years. When the reservoir has got filled up with deposits to the extent which is considered a maximum, the workmen enter the under-sluice, bore with an auger through the door to be sure that the mud is solid, saw the timbers B, C and D, and then escape into the gallery. The door is now free to drop, but it is generally held by the solidified mud. The workmen now go to the top of the dam and work a hole through the deposit with a long iron pole until the water touches the door. When this happens the door falls, and the mud follows it in a tremendous avalanche. The reservoir is soon emptied, and more or less of the deposit

removed. A new gate is then put in, new horizontals B, C, D are placed behind it, and the reservoir begins to fill again."[1]

Recognition of the liability to obliteration by deposit of silt, to which most reservoirs formed by solid dams are subject, led to the design of an insubmergible dam pierced with numerous

BHATGARH DAM
SECTION
THROUGH UNDER SLUICES

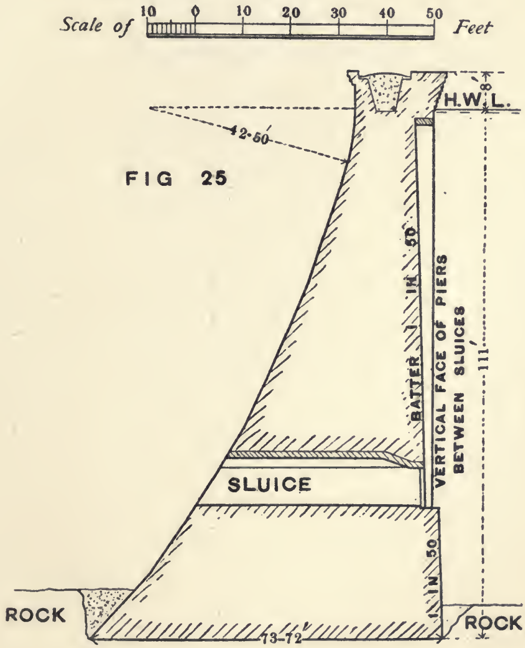


FIG 25

under-sluices. The first specimen of this class of dam was the Bhatgarh dam in India (Fig. 25), constructed about 1892. This dam has a maximum height of 127 feet. There are two overflow waste weirs, one at each end of the dam. But there are also 15 under-sluices, each 8 feet by 4 feet, piercing the dam near its centre, with their sills 12 feet only above the bed

[1] "Perennial Irrigation, etc.," Government of Egypt (1894).

of the river, which is 103 feet below the crest of the dam. The object of these sluices is to prevent the deposit of silt in the reservoir by providing a passage for the early floods at a low level. If the flood water, heavily laden with silt, were to be discharged over the high level waste weirs, it would drop the greater proportion of its silt on the bed of the reservoir in its passage through the deep pond above the dam. In ordinary floods the discharge through the under-sluices is effected under a head averaging 15 feet, and the ponding up extends to a distance of 3 miles above the dam. Consequently a certain proportion of silt will be deposited in the reservoir, even when the under-sluices are open to pass the early floods. But as they are closed on July 31st, or earlier, to ensure the filling of the reservoir, there will be a further deposit due to the later floods which enter the reservoir basin after the low level exit is closed. Still it is a great point gained that, at the time when the floods are carrying the greatest amount of silt, the discharge is allowed to flow forward through the reservoir with a comparatively small heading-up. The surface of the backwater, when the under-sluices are open and working under a head of 15 feet, is less than one thirtieth of the area of the reservoir when full; and, therefore, twenty-nine thirtieths of the reservoir bed are out of the reach of silt deposit. On the remaining thirtieth under water there is also less tendency to deposit than there would be if the discharge from the reservoir had to find its way over the high level waste weirs. Undoubtedly the action of the under-sluices will be effectual in prolonging the life of the reservoir: the experience of the last thirteen years has demonstrated this.

The principle of allowing the silt-laden waters of floods to pass through the reservoir basin without serious diminution of velocity has been applied in a more thorough-going way to the design of the Assuan dam on the Nile. This dam (Fig. 26) is remarkable as being the first insubmergible dam built without any provision of overflow waste weirs to discharge excess water.

ASSUAN DAM.

The whole river discharge at all times of the year is passed through sluices pierced in the body of the dam, as may be seen on Plate I., which is a reproduction from a photograph taken by the author on the day after the inauguration of the dam. The dam is also remarkable on other accounts. It is about $1\frac{1}{4}$ miles long, and contains over a million tons weight of masonry.

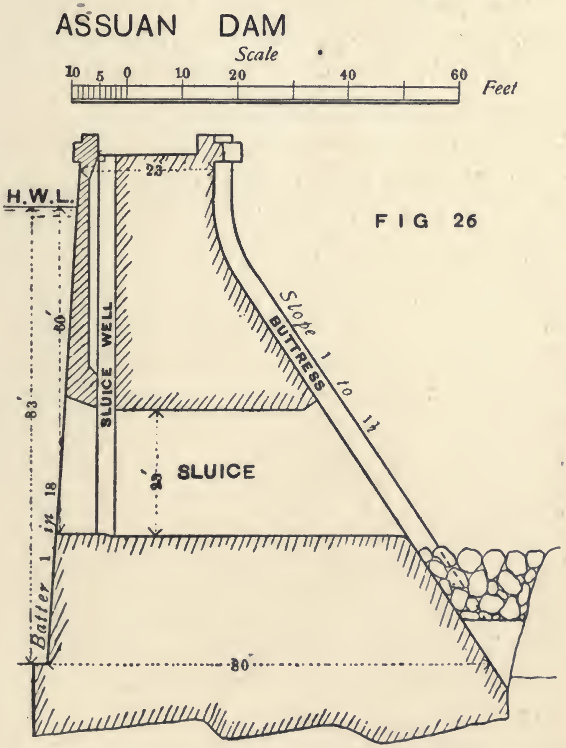


FIG 26

Moreover, the available capacity of the reservoir, formed by it in the trough of the Nile itself, for a length of 140 miles, is greater than that of any artificial basin in the world. The gross capacity of the Bhatgarh reservoir (Lake Whiting) in India is said to be 40,000,000,000 cubic feet, but this can scarcely be reckoned as *available* capacity, since the reservoir is only expected to fill once in thirty years. But the present

possibilities of the Assuan reservoir exceed that figure. The capacity of the reservoir, according to the calculation made by Sir William Willcocks, the designer of the dam, is 37,611,000,000 cubic feet (1,065,000,000 cubic metres). But, without any alteration to the dam, the full supply of the reservoir can safely be raised 10 feet above the level used in the calculation which gave that figure, and the available capacity be thereby increased to about 50,000,000,000 cubic feet. The greatest height of the dam is 127 feet. It supports a head of water of 67 feet, which may safely be made 77.

The past history of reservoirs is sufficiently full of warnings of the danger that would be run if a solid dam were constructed to impound such a river as the Nile. During the flood months of August and September, and sometimes October, the Nile water is heavily charged with matter in suspension. Any obstruction such as a solid dam, which materially interfered with the flow during those months, would inevitably induce a heavy deposit of silt, and eventually cause the obliteration of the reservoir basin. The dam might survive, but merely as a picturesque waterfall like the Spanish dam of Val de Infierno. To avoid this danger, the Assuan dam was designed to pass the whole Nile flood through under-sluices. Of these there are 180 in number, all of them 2 metres (6½ feet) wide, the 40 upper sluices being 3·5 metres (11½ feet) high, and the 140 under-sluices 7 metres (23 feet) high. They are placed in groups at four different levels in the dam, a convenient arrangement for regulation. The maximum velocity of discharge through a sluice will be that due to a 9 metre (29½ feet) head; that is to say, 10·5 metres (34½ feet) per second. An extreme flood of 14,000 cubic metres (494,500 cubic feet) a second, which comes but seldom, would be passed through the under-sluices, all being open, with a heading up of about 3·5 metres (11½ feet) and with a resulting velocity of about 6½ metres (21⅓ feet) per second. An ordinary flood will be passed with a heading up of 2 or 3 metres (7 to 10 feet) only. Thus the turbid

flood discharge will be scarcely interfered with, and there will be no danger of serious silting. Under normal conditions of the river discharge the sluices remain open till the end of October, when the water becomes comparatively clear. During November, December and January the reservoir is filled by the gradual closure of the sluices, commencing first with the lowest groups. During February and March the reservoir is kept full; and in April, May and June its stored water is drawn upon to supplement the deficient discharge of the river. Before the end of July all the stored water has been discharged, and all the sluices are open ready to pass the rising flood.

It has been explained in the preceding chapter that Egypt is in want of more water than the Assuan reservoir supplies, and that a proposal to raise the dam has been under consideration. It was estimated that an extra height of 6 metres (or nearly 20 feet) added to the dam would double the storage capacity of the reservoir. The resulting stresses in the masonry were accordingly calculated by the hitherto accepted method, and it was found that the usual conditions of stability would be complied with if the dam were raised by the proposed amount. The maximum pressure on the masonry, as the structure now stands, is calculated to be 4 tons per square foot on the down-stream side with the reservoir full, and 5·8 tons per square foot on the up-stream side with the reservoir empty. These are low pressures with so large a margin of safety that the raising of the dam might be undertaken without danger if the resulting increase of these pressures were the only consideration. But unfortunately that is not so. The Assuan dam had been in action for two years when the question of raising it came up for decision. During that time the severe action of the water, discharging through the sluices with a high velocity, had eroded the sound granite beyond the down-stream toe of the dam. To have raised the dam and to have thereby added to the head of water would have increased the severity of the erosive action of the sluice discharge. As extensive protective

works, estimated to cost about a quarter of a million pounds and to take two years to complete, were necessary to secure the dam, as it stood, against danger from erosion of its natural granite talus, the decision as to the raising was postponed till this work should be complete. The granite bed of the river below the sluices had been originally left in its natural rough state with an irregular surface: it has been found necessary to substitute an apron of masonry in cement mortar with a smooth surface to protect the rock from the shock of the falling water and to support the toe of the dam. The photograph, reproduced as Plate I., shows in the foreground a group of the upper sluices and the rough granite of the river bed on which the water falls.

The postponement of the consideration of the question of raising the Assuan dam had another advantage. It gave time for the further investigations of Professor Pearson's and Mr. Atcherley's new theory concerning stresses in dams, which will be found stated shortly in an abstract of Mr. L. W. Atcherley's Paper, published in Vol. 162 of the Proceedings Inst.C.E., November, 1905.

In the Assuan dam there is no waste weir or outlet sluice; the under-sluices take their places. In the Bhatgarh dam the under-sluices do only a small part of the work of passing the reservoir discharge, and are in action for a short period only during the year; the waste weirs of the crest, on either flank of the insubmergible portion of the dam, provide for the outflow from the reservoir for the rest of the year. Submergible dams have no separate waste weirs, being themselves waste weirs. But insubmergible solid dams and earthen dams must have their waste weirs, and care must be taken that the discharging capacity of these weirs be ample. The neglect to provide sufficient waterway for surplus water to escape has caused the ruin of not a few dams. If the waste weir is high, it often takes the form of a submergible dam, as in the case of the overfall portion of the Croton dam (Fig. 14). Some weirs have no crest shutters, discharging capacity being obtained by

length of crest with shallow depth of overflow. But sometimes it is more convenient, from want of space or for economical or other reasons, to increase the depth of overflow rather than the length of weir. In the waste weirs of the Bhatgarh dam many of the vents are fitted with the automatic gates invented by Mr. Reinold. Fig. 27 shows the principle upon which these

REINOLDS AUTOMATIC

SLUICE GATE

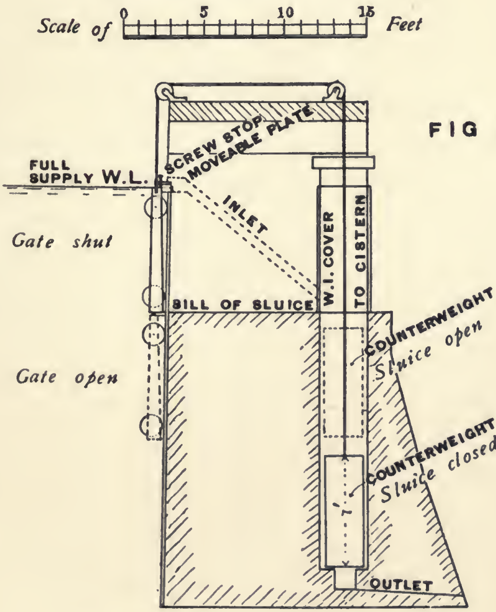


FIG 27

gates work. Each gate is suspended by chains connecting it with a counter-weight which is free to move up and down in a water-tight chamber formed in the thickness of the weir wall, An inlet pipe admits water to the cistern when the reservoir is at full supply level, and an outlet pipe at the bottom allows it to escape. The discharge of the outlet pipe at its maximum is less than the maximum discharge of the inlet pipe. It will be observed from the drawing that the sluice is closed when the

gate is raised. The automatic action is produced by water finding its way to the cistern and reducing the lifting power of the counter-weight through immersion. When the water in the reservoir rises to the level of the inlet pipe, the cistern gradually fills and the counter-weight is immersed. When the counter-weight has in consequence lost sufficient weight, the gate becomes the heavier and moves downwards below the level of the sluice sill, and continues to do so as long as the water rises in the cistern. When the discharge through the opened sluice lowers the water in the reservoir below inlet level, the cistern empties itself of water by its outlet pipe, and the counter-weight regains the weight necessary to pull up the gate and close the sluice.

Before leaving the subject of dams, it may be useful to give the figures representing the actual maximum pressures on the masonry in some existing dams, selected from among old and recent ones.

Name of Dam.	Maximum Pressure. Tons per Square Foot.	Weight of Masonry. Pounds per Cubic Foot.
Almanza, Spain	12·83	—
Alicante, Spain	10·34	—
Verdon, France	5·80	—
Gros Bois, France	14·60	—
Bhatgarh, India	7·27	160
Assuan, Egypt	5·80	143·5
Marikanave, India	*8·00	150
Mundaring, Australia . . .	*8·00	—
Quaker Bridge, New York . . .	16·60 (designed)	(New Croton dam substituted)

* Pressure not to be exceeded in accordance with conditions laid down for design.

Wilson's "Manual of Irrigation Engineering" gives the following values for the limiting pressures which are ordinarily accepted as safe to allow :—

Brick . . .	7·70 tons per square foot.		
Sandstone . .	8·35	,,	,,
Limestone . .	9·80	,,	,,
Granite . . .	10·00	,,	,,

From six to eight tons per square foot may be taken as the pressure generally considered permissible in important dams of recent construction. Bold things, however, are done in America, and the New Croton dam may show that engineering practice in the design of dams has erred on the side of caution. It will be observed that the pressure allowed for the Marikanave dam in India and for the Mundaring dam in Australia is half that allowed in the design of the New Croton dam, New York.

CHAPTER VI.

MEANS OF DRAWING ON THE SUPPLY.

THE supply of water, as already pointed out, may be drawn from wells, rivers, natural or artificial reservoirs, or tanks. When a storage reservoir forms a feature of an irrigation system, the supply drawn from it may either be carried to the distributing channels from which the lands are irrigated in a canal or canals taking off direct from the reservoir itself, or be sent on its way along the natural channel of the river to the point where the canal system takes off. It is only from the smaller class of reservoirs, which are called tanks in India, that the distributaries are fed direct. The low-lying reservoirs of the United States, which are filled during the flood season by canals taking off from a river, may be classified as "tanks"; they deliver their water direct to the channels that distribute it to the fields.

When wells are the source of supply, various mechanical means are used to raise the water. For small lifts the *shadouf* of Egypt—the *lât* or *picottah* of India—is commonly used; for deep wells in India the *mote* is substituted; for medium lifts the Egyptian *sakia* or Persian wheel is universal. The *shadouf* and *sakia* are also used extensively along river margins for the irrigation of small holdings. The province of Dongola, at one time reputed to be the richest province in the Sudan (a reputation of no very high order), is irrigated almost entirely by *sakias* along the river edge, assisted by a very few only on wells. This province will therefore furnish reliable statistics of what a *sakia* is capable of doing, and it is worth while to note the figures. In 1904 there were at work in Dongola 3,892 *sakias*, 3 pumps

WATER-LIFTING UNDERSHOT WHEEL, EGYPT.

driven by engines of an aggregate of 50 horse-power, and 51 *shadoufs*. The 50 horse-power pumping plant and 51 *shadoufs* may be assumed to be equivalent to 58 *sakias*, bringing the total number of *sakias* up to 3,950. The area of taxed land in 1904 was 58,057 acres. The population was 130,000 souls, inclusive of merchants, tradesmen, mechanics, etc. So that there was 1 *sakia* to every 15 acres of taxed area, and 2·24 persons per acre or 33 per *sakia*. Apparently the area under cultivation had reached the limit that the population was capable of taking in hand, as there was at least three times that area of cultivable land available in the province, of which two-thirds was lying fallow.

The area of crop that each of the contrivances named can keep watered is small, and naturally varies with the lift. A single *shadouf* is only equal to the irrigation of one or two acres of crop; a *mote* or *sakia* can irrigate, on the average, eight acres.

Shadoufs are often worked in tiers, one above the other, so as to effect a total lift of 15 feet or more. The Persian wheel and the *mote* can be readily adapted to varying heights of lift by altering the length of the endless chain carrying the water buckets or pots in the one case, and of the rope and bullock run in the other.

These primitive watering contrivances of the East are well adapted to farms of quite small areas, and to communities wanting in mechanical skill and possessed of no appliances for the handling of more elaborate machinery.

It is an idea that suggests itself to most who give their minds to irrigation problems that the energy of the wind could with advantage be utilised to raise water. But the wind is a more capricious servant for irrigation to rely upon than rainfall. In Holland windmills for lifting water are becoming obsolete: the reliability of pumping stations worked by steam power has discredited the qualifications of the wind. But in the arid west of the United States wind power is not despised, as its cost is about two-thirds of that of steam power. A windmill in

America can be depended upon for the irrigation of about three acres; but if a tank, to act as a reservoir to store water at times when irrigation is not being carried on, is associated with the windmill and its pump, from five to fifteen acres can be given irrigation. This contrivance also is, therefore, only suited to small holdings, and to irrigation on a very modest scale.

In the Fayum Province in Egypt and on the Genil river in Southern Spain undershot wheels, carrying pots or buckets at their circumference, are made use of to lift water on to high lands alongside. An ordinary lift for such wheels is 15 feet. The amount of water lifted for each revolution of the wheel is small, but the delivery into the high level trough is continuous. To work the wheel a drop of from 2 to 3 feet is required. Plate II. gives a view of one of these wheels in Egypt, and Plate III. of a similar wheel in Spain.

For large estates and irrigation on an extensive scale some more efficient means of drawing on the supply must be employed. In Egypt the introduction of cotton and sugarcane cultivation brought so much gain to the farmer that he was able to afford a centrifugal pump, worked by steam power, for the irrigation of his crops. Sir William Willcocks, in "Egyptian Irrigation" (1899), gives the number of such pumps as nearly 4,000. Twenty-one years ago the Egyptian Government itself was on the point of adopting powerful pumping stations as the sole means of drawing its water supply from the river, and had actually made a commencement of putting that policy into practice, when better counsels prevailed. For, when irrigation is on the scale of the Government system of Egypt, there is a more effective and economical way of getting the river water into the canals than by pumping it. The method consists in raising the low water level of the river by wholly or partially damming its summer channel, so that the required discharge may be forced to flow into the canal or canals taking off from above the dam. By this means the difference of level between the land and water surfaces at the canal head is

WATER-LIFTING UNDERSHOT WHEEL, SPAIN.

diminished. The canal, connecting the pool above the river dam and the land to be irrigated, is given a water surface slope of a less gradient than that of the land surface, so that, after a certain distance from the canal head, land and water surface come to one and the same level.

The means employed for heading up the summer level of the river at the canal offtake will first be considered. Different countries seem to have their own peculiar type of work by which this heading up is effected. The Indian type is the "anicut," a submergible solid weir, over which the flood flows, the control of the levels and currents being provided for by what are known as under-sluices, or scouring sluices, on one or both flanks of the weir, and sometimes also in the centre. The Egyptian type is the "barrage," of French origin, as its name betrays. A barrage may be described as an insubmergible river regulator, formed of piers resting on a platform at river bed level and rising above flood level. Vertical grooves are built into or cut in the piers, and shutters slide up and down in them. By lifting or lowering the shutters the level of the water in the pool above the barrage is controlled. In flood-time all the shutters are lifted above the water level, and the river flows unchecked through the vents. For general convenience, arches are turned between the piers, and a roadway is thus provided between the two banks of the river.

In France there are several types of river regulators of ingenious, and sometimes elaborate, designs. The early Poirée dams were of the needle kind with iron trestles as supports to take the pressure of the water when the needles were in place. The Boulé shutters later on were substituted for the needles, the Poirée frames being retained. The Boulé shutters are merely sluice gates, lying one above the other in tiers vertically and side by side in rows horizontally, fitted each one with a bent iron strap whereby to get hold of and raise it. Another form of closure is the Caméré curtain,[1] which consists of narrow

[1] "The Improvement of Rivers," by Thomas and Watt.

horizontal strips of wood hinged together and capable of being rolled up by a chain which passes round them, each curtain reaching from the surface of the water to the sill, which is near river bed level. The curtains are supported by frames, which either lie flat on the floor during flood, or are lifted up clear of the water by overhead machines, so that the river passes freely without obstruction of any kind. These systems, however, suffer from the usual delicacy that attends complication of structure, and, moreover, are ill adapted to rivers in which there is floating debris. To obtain a tight closure when any debris has clung to the frames is an impossibility with the Caméré curtains and a difficulty with the Boulé shutters.

The "Chamoine" system, of French origin, has been imported into America, and good examples of this form of regulation are to be found on the Ohio and on other rivers in the States. The "Chamoine" apparatus consists essentially of three parts, viz., the shutter itself, the pivoted frame on which the shutter rides, and the strut. The sill is formed of a narrow ridge on the floor. The bottom of the shutter, when erect, bears against the up-stream edge of the sill. The frame, or "horse," upon which the shutter rides, moves about its pivots on the floor immediately down stream of the sill. The shutter is hinged near its middle to the outer end of the "horse" about which it revolves, and is free to assume any position between a horizontal and a vertical one. The strut supports the shutter and its "horse" when they are raised and in the closed position. The lower end of the strut rests against a casting on the floor. When this is moved from the strut end, the shutter falls under the pressure of the water, turning about its hinge along the upper end of the "horse" until it lies flat behind the sill with "horse" and strut beneath it.

In America irrigation on a large scale is of comparatively recent growth. Practical experience with old and new ideas in the design of irrigation works, and the lessons of experience in a country quick to learn, will doubtless, in due time, result in the

DAM ON THE RIVER GENIL, SPAIN.

evolution of a form of river regulator which will be recognised as the American type. "Rock-fill" and "crib" weirs can only be considered as works of a temporary nature, destined to be replaced by more permanent structures when and where the interests affected are important enough to justify and to bear the increased cost of construction.

Perhaps the best known irrigation system in Spain is that which serves the fertile plain of Granada, stretching away from the foot of the hill on which the Alhambra stands. Here, round about the last foothold of the Moors in Spain, are to be found swift-flowing canals meandering along the steep hill-sides and through intercepting rocks down to the green plains beyond the town of Granada. The water is derived from the river Genil and its tributary the Darro, which joins it at Granada. The head works of the canal system are primitive in the extreme, and are probably as they were in the time of the Moors. Plate IV. shows the regulating dam across the river Genil below the head of the principal canal. It is constructed of weighted trestles of the form shown in Plate V., which is the photograph of a spur made at a spot a short distance above the site of the dam. But the dam, though primitive and in need of restoration after every severe flood, is efficient, if it is to be judged by the results that are visible from the Alhambra gardens.

The selection of a site for the river work which is to hold up the water will depend upon many things. The work must naturally be at such a point on the river that the canal which takes off from above it shall deliver its water at country surface at the upper limit of the land to be irrigated "free-flow," that is, by gravitation or simple flow without the necessity of any lift. The distance from the first point of irrigation should, for the sake of economy, be as short as possible consistently with the fulfilment of the condition concerning the delivery of water at country surface. But it is not always possible to secure the minimum. The material of the river bed, its cross section, the

direction of the channel above and below, the nature of the river banks, and much else, will have to be taken into consideration in the selection of the best site. In the case, however, of a river work intended to head up water for the canals of a deltaic system, the selection of a site is restricted to comparatively narrow limits, as the work must of necessity be placed at the head of the delta where the river throws off or divides into branches.

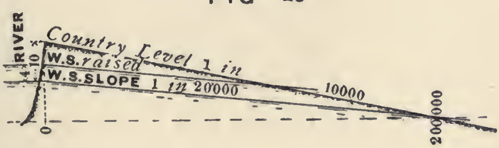
The height to which the summer level in the river is to be headed up must be first decided. The greater the heading up, the shorter will be the length of canal along which the water must flow to come to ground level. The usual head for a river regulator is from 10 feet to 13 feet. In Chapter II., a figure (No. 5) was given showing the principle of grading a canal fed by a river in flood, so that, after the necessary length of flow, the water should spread itself over the land. In flood the natural levels of the river, under the conditions assumed in the figure, are only a few feet below country level, so that, after a comparatively short run, the water in the canal comes to country level. But in summer the levels of the river are so low that, if a canal takes off from it at its natural level, it will have to flow a long distance before its water comes to land surface. So it is better to raise the river level artificially, and reduce this unprofitable length of canal. Supposing, for example, that the country level is 10 units above summer water level, and that it has a slope in the direction that the canal will take of 1 in 10,000 units. If, in such a case, the canal is designed to flow with a water surface of 1 in 20,000, then the summer water will come to the land surface after a run of 200,000 units, or—adopting, for convenience' sake, metres as the unit—200 kilometres (Fig. 28). Now, supposing that the summer level of the river is artificially raised 4 units, or metres, the canal water comes to land surface at a point 120,000 units, or 120 kilometres, from the head instead of 200 kilometres. This arrangement results in a great saving of

RIVER SPUR, SPAIN.

expenditure on the earthwork of the canal excavation, balanced to some extent by the cost of the head works in the river. But, neglecting the question of economy, this advantage has been gained, namely, that the country between kilometres 120 and 200, or on a length of 80 kilometres, is now commanded by the canal and can be given free-flow irrigation. The diagram (Fig. 28) shows the country level and the summer water levels as they would be with and without artificial heading up of the river.

It has been stated above that 10 feet to 13 feet is the usual amount of heading up that river regulators are called upon to effect. But there is a well-known work in Egypt—the Delta barrage—which, with the help of a recently built subsidiary weir below either section of it, now holds up 20 feet, each

FIG 28



work undertaking half the head. If a project contemplated so considerable a heading up as this, the division of the head between two separate works would probably be considered advisable, and the Delta barrage principle be imitated. For a single work it has hitherto been considered wise to limit the head to 13 feet when the work has to be founded on the ordinary sandy bed of a river. But the "Grand Anicut" of Madras, which is said to have been constructed sixteen hundred years ago, and which was until quite recently in effective use, had its crest 15 to 18 feet above the bed of the river, though composed only of rough stone set in clay without mortar of any kind. The Kistna weir, built in 1855, has its crest 16 feet above summer level and 25 feet above the deepest part of the original bed.

In deciding upon the design of the river regulator, the effect

that the obstruction, which it creates in the river channel, will have on the flood discharge must be carefully considered. If the backing up of the water, or "afflux," should be considerable, there may be danger of causing inundations in consequence of the higher flood levels produced, and danger, perhaps, of the flanks of the river work being turned by the flood water. The solid immovable part of the regulator, which remains through the flood, must not therefore obstruct so great an area of the flood waterway as to affect the high water levels inconveniently. In the case of the Egyptian barrages and regulators of the French type, the obstruction offered to the flow is slight, as the shutters which effect the heading up at low supply are removed clear of the water during flood. The design of the French types provides for the removal also of the supports against which the shutters bear.

In India, where the regulator takes the form of a solid weir called an anicut, it has been found, as the result of experience, that the afflux is not the only effect of a solid obstruction that makes it desirable to limit the height of the weir. In the case of anicuts of ordinary height, many examples of which exist in India, the afflux in flood is not sufficient to be a serious objection. But in several cases it has been found that the obstruction of the flood waterway causes irregular silting up of the river bed above the anicut, and that the summer channels are inconveniently affected thereby. Sometimes on this account, and sometimes from other causes, a sufficient discharge could not be forced into the canals at low supply; consequently, in such cases, it has been found necessary to add crest shutters along the whole length of the anicut to raise the summer level still higher, so that the river water may flow into the canals. These shutters are so designed that they may be laid flat in the flood, and not cause any additional obstruction to the flow. Profiting by the lessons taught by experience, the irrigation engineers of India have recently shown a preference for low weirs with crest shutters, and the later designs take this

form. The crest shutters are usually from 2 to 3 feet high, but in some cases are 6 feet high.

An anicut is made up of the weir proper and of one, two, or more groups of "under-sluices." These "under-sluices" are regulating openings in the weir, divided up into bays, fitted with some form of regulating shutters. They are sometimes called "scouring sluices," a term to be preferred to the more commonly used "under-sluices." The floor of the sluices is generally about river bed level. It was expected by the original designers that the control of the flood currents, which the power of opening and closing the sluices would give, would make it possible to maintain the deep channels of the river along such lines as might be desired, and that silting up of the river bed above the weir would be prevented. But the influence of the under-sluices has been disappointing, and the expectations have been only partially realised. In the case of the Sone anicut in India, under-sluices were provided on each flank of the weir, below the offtake of the canals on the right and left banks of the river, in order to create a draw past the canal heads. There were also added (but not without misgivings) under-sluices in the centre of the weir, which were expected to prevent silting above the weir and to maintain a navigable channel across the river. They have done neither; and so, as they were very troublesome to manipulate, they have now, after being in use for thirty years, been permanently built up.

The difficulty caused by the irregular silting of the river bed above an anicut may be lessened in some cases by a judicious selection of the anicut site. A straight reach of the river, where the cross-section is constant and the velocity of flow uniform, offers favourable conditions. A site where the river is abnormally wide, though it may afford facilities of construction, is not favourable to the prevention of irregular silt deposit. It would be better, if such conditions offer, to select a site where the general width of the river is rather less than the normal as the one most likely to be free from the silt trouble. The

increase of velocity over the weir itself, due to less length, might necessitate somewhat heavier stone in the talus; but, if so, the expense would be balanced by the economy resulting from the shorter length of weir. But, though the average rate of flow would be greater in the shorter weir, the maximum velocity might even be less, as the flow over the longer weir would not be so uniform in consequence of the silt deposit above it interfering with the even flow. It is *irregular* silting that is objectionable as giving rise to currents which are not at right angles to the line of the weir and which may besides have locally a high velocity. Uniform silting against the weir along its up-stream face and over the adjacent river bed is beneficial as adding to the strength and impermeability of the work.

In all cases in which the bed of the river is sandy, the weir should be built at right angles to the direction of the stream. There are exceptional cases, where the river bed is rocky or strewn with boulders, and the river velocity is high, in which it may be advantageous to adopt an alignment inclined to the stream. Figs. 29, 30, 33, 34, and 35 give cross-sections of those weirs of the Indian type which have been selected as examples of the different varieties of design adopted. The weir below the Delta barrage is given as the Egyptian variety, the design being based on that of the Sone weir, but having its own points of originality. The different varieties are classified as follows:—

(1) Weir with vertical drop on to impervious floor: to this class belong the Narora, Burra, and Baiturnee weirs;

(2) Weir without drop, but with impervious floor sloping downwards from the weir crest: to this class belong the Chenab and Godavery weirs;

(3) Weir without impervious floor or drop, but with slope of stone with open joints inclined downwards from weir crest: to this class belong the Sone, Mahanadi, Brahmini, Kistna, and Okla weirs, and also the Egyptian weir.

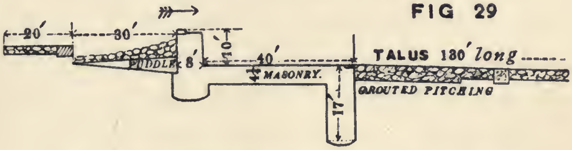
The Narora weir has been selected as an illustration of the

first class, for it has a record which is instructive. It was originally built as in Fig. 29. A weir of this description, in common with weirs of the other classes, has to guard against the danger of the overflow scouring holes in the river bed along the down-stream toe of the talus, and cutting backwards till the main body of the work is reached and undermined. The deep curtain wall along the down-stream edge of the floor of the Narora weir was designed to meet this danger. But a curtain wall in such a position does not give absolute security; it is, at

NARORA WEIR

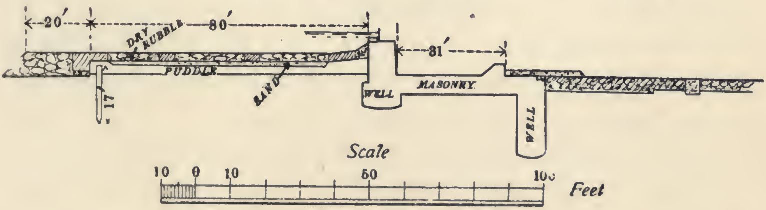
AS ORIGINALLY CONSTRUCTED

FIG 29



AS STRENGTHENED

FIG 30



best, but the second line of defence against the scour which may threaten the stability of the work. The talus of heavy stones is the first line of defence, and whenever any of this is displaced in consequence of the scouring out of holes by eddies, or through the sweeping away of the stones by the high velocity current, the holes must be filled up and the slope re-made to its original height, with still heavier stones than before if found necessary.

Another danger to which weirs in general are subject is leakage under the weir main wall or floor, known as "piping."

When subjected to a head of water there is always, in the case of weirs built in sand, movement of water under the weir from up stream to down stream. But if the resistance encountered is sufficiently great, the rate of flow is so low that the foundation bed of the weir is not disturbed. Should, however, a run be created in which the velocity of flow is high enough to carry along grains of sand, by degrees the leak will increase until it undermines the weir and causes its failure. The failures of the under-sluices of the Mahanadi weir in 1886, and of the Chenab weir in 1895, were ascribed to this cause; and the Delta barrage in Egypt suffered from the same defect in 1867. This form of danger is aggravated by the scouring action of parallel currents whenever they establish themselves along the front of the weir from faulty alignment or other cause. Such action must be guarded against by constructing long spurs at right angles to the weir to guide the flow into the right direction.

But, besides these dangers common to most weirs, the form of which the Narora weir is an example has two other forces to resist. The one is the force of the water falling on to the floor over the weir wall; the other is the force exerted on the under-side of the floor, tending to lift it, due to the pressure developed when the weir is holding up a head of water. The first is easily met by giving the floor sufficient thickness and covering it with ashlar blocks.[1] If the ashlar is properly bedded, there need be no fear of failure in the case of a weir of slight fall, such as anicuts have, in consequence of the action of the water falling on its floor surface. But the other form of force, which is applied to the under-side of the floor, is not so easily disposed of, and its mode of action must be carefully studied. The Narora weir is a useful example for consideration, for it failed in 1898 from the inability of its floor to resist the upward pressure.

The upward pressure, due to the head on the weir, decreases in its transmission through sand in proportion to the distance

[1] But see remarks on p. 141 concerning ashlar coverings.

travelled. It is a maximum at the starting-point, and nothing at the point where it finds an exit below the weir. The pressure at any point can, therefore, be found by drawing a right-angled triangle with its base representing the path which the water has to travel between the starting-point and the point of exit, and with the perpendicular to the base representing the head of water. The "hydraulic gradient" is then represented by the hypothenuse of the triangle, and the pressure at any point along the path of the water by the line drawn perpendicularly from the corresponding point of the base to the hypothenuse. If, for example, the path of travel is 100 feet and the head 12 feet, then at 25 feet distance from the starting-point the pressure will be that due to a head of 9 feet, at 50 feet distance to a head of 6 feet, and so on. Thus it will be clear that the shorter the path the steeper will be the hydraulic gradient, and, therefore, the higher the rate of flow. The path of travel is assumed to follow the face of the masonry, whether it is horizontal or vertical.

But the line representing the hydraulic gradient would not, under all conditions, be a straight line. If loose gravel were the material through which the percolating water passed, the hydraulic gradient, or pressure slope, would probably be steep at the upper end and flat at the lower; if fine clayey soil were the material, the slope might be flat at the start and steeper at the finish. With sands of ordinary resistance the normal slope may be taken to be a straight line, on either side of which curves, more or less divergent, would represent the pressure slopes for different materials.[1] In the following remarks about the Narora weir, it is assumed that the conditions affecting percolation were normal, and that the hydraulic gradient is correctly represented by a straight line. The general principles to be deduced will not be affected if the assumption in this case is not strictly correct.

[1] "Note on Passage of Water through Sand," by Lieut.-Col. J. Clibborn, I.S.C.

Only a few days before the floor of the Narora weir was lifted two pipes had been fixed in the floor in communication with the under-side at the points shown in the accompanying sketch (Fig. 31), with the object of ascertaining the pressure by direct observation, as some doubts were entertained concerning the stability of the work. The insertion of the pipes had nothing to do with the accident, as that occurred in a quite different part of the weir. At the time of the experiment the head on the weir was about 12 feet. The height to which water rose in

NARORA WEIR

SHOWING OBSERVATION PIPES

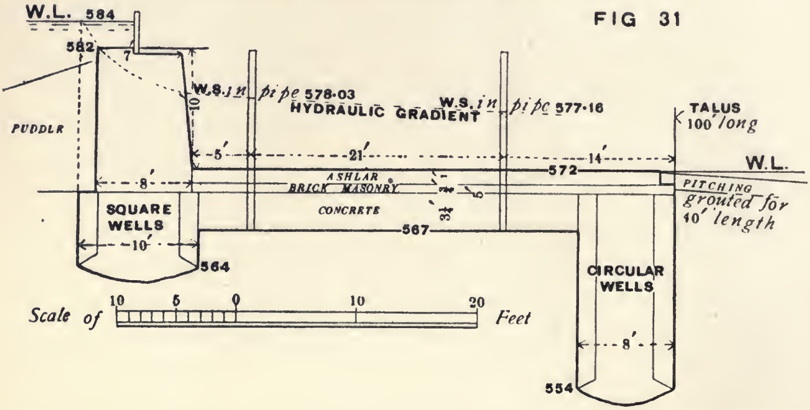


FIG 31

the pipes showed that, at a point about 13 feet from the up-stream face of the weir wall, the upward pressure was that due to a head of 11 feet of water; and that 34 feet from the same face the pressure was that due to a head of about 10 feet. Such being the case, and the floor being only 5 feet thick, matters would be critical when the river bed below should become dry. Mr. Buckley thus describes the giving way of the floor: "At the time of the accident a strong spring burst through the floor at the toe of the crest wall, and, passing under the stone flooring, lifted it bodily over a length of 340 feet to a maximum height of 2·23 feet. The weir wall

settled, in a length of 120 feet, about 3 inches, and the flooring showed vertical cracks. The grouted pitching below the floor was 'blown up.' Up stream of the part of the weir which was damaged the apron had disappeared, and the wall was exposed to a depth of 8 or 9 feet. Borings through the floor revealed cavities below it extending to about 50 feet on each side of the point of fracture." The original puddle up stream of the weir wall had, previously to the accident, been scoured out, and had been replaced by block kunkur. Consequently the starting-point of underneath flow was against the weir wall itself.

The cause of the accident was clear enough. The upward pressure was too strong for the floor, or the floor was too weak to resist the upward pressure. There were two possible remedies: either to make the floor strong enough by building on the top of it, or to reduce the pressure under the floor. The latter was the remedy adopted. The starting-point of underneath flow was removed 80 feet up stream, and thereby not only was the pressure under the floor reduced, but the hydraulic gradient was considerably flattened out—conditions favourable to stability and prevention of "piping." This result was obtained by adding up stream of the weir wall an apron of puddled clay 2½ feet thick, with its surface and up-stream end protected from scour by a layer of pitching and a bounding wall of kunkur masonry, as shown in Fig. 30. The up-stream face of the weir was secured against the danger arising from parallel currents by the construction of additional groynes to act as guiding spurs. A dwarf wall, 3 feet high, was added along the down-stream edge of the floor to form a cushion of water below the drop of the weir wall. This cushion would also have the effect, when the river bed below the weir was dry, of adding weight to the floor, and of counterbalancing 3 feet of the upward pressure.

The condition of things at the time of the accident, as well as since the additions, is shown in Fig. 32. It will be seen

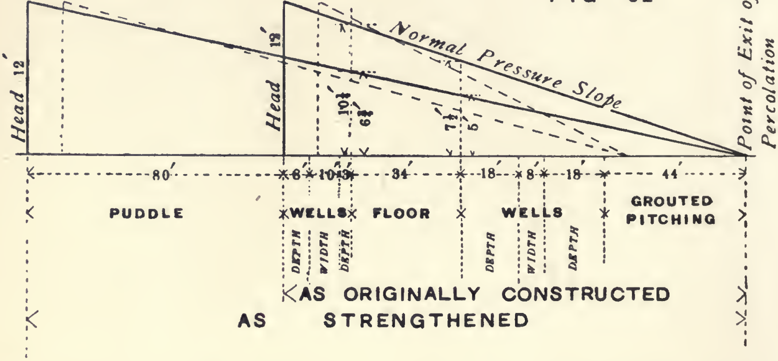
from the diagram that the upward pressure on the floor below the drop has been reduced from $10\frac{1}{4}$ to $6\frac{3}{4}$, that is, to a pressure due to $6\frac{3}{4}$ feet head of water, of which 3 feet is balanced by the water cushion on the floor. So that there remains a head of only $3\frac{3}{4}$ feet to be resisted by the effective weight of the masonry floor of 5 feet thickness (*i.e.*, gross weight of floor less the weight of water displaced).

Another advantage of extending the impervious part of the work on the up-stream side of the point where the heading up is

DIAGRAM

TO SHOW PRESSURES ON FLOOR OF NARORA WEIR

FIG 32



effected is, that the extension can be economically made of clay puddle, as the upward pressure is more than counterbalanced by the weight of water above. Clay puddle, with its surface protected from scour, is as good as, or better than, masonry in such a situation. In fact, if it were not for the necessity of resisting the pounding and scouring action of the water down stream of the point of heading up, the impervious part of the work might all be up stream. The full lines of the diagram of the hydraulic gradient and pressures (Fig. 32) have been drawn on the assumption that the water has to pass underneath the deep curtain wells; but as the interstices between wells,

especially circular ones, are difficult to make water-tight, the path of the water probably passes *between* the wells. If the depth of the wells is excluded from the path, the hydraulic gradient will have a shorter base and will become steeper, as shown by the dotted lines. It will be found that, with this correction, the upward pressure at the point below the drop wall was that due to $10\frac{3}{4}$ feet head before the addition of the up-stream apron, and is now 6 feet.

A consideration of the diagrams, Figs. 31 and 32, leads to the following conclusions:—

(1) That extension of the impermeable platform up stream of the drop wall decreases the upward pressure on the floor below the drop wall at the same time that it reduces the steepness of the hydraulic gradient and, therefore, the rate of flow of the percolation water;

(2) That extension of the impermeable platform down stream has the disadvantage of increasing the upward pressure on the floor below the drop wall, though the steepness of the hydraulic gradient is favourably affected in the same way as by an up-stream extension;

(3) That for these reasons a curtain wall is well placed if up stream of the floor, but badly placed if down stream, except as a precaution against cutting back and undermining of the floor; and—

(4) That it is a mistake to grout pitching on the down-stream side of the floor, unless the pitching cannot be otherwise made strong enough to resist scour, it being assumed that the water-tight floor below the drop wall is made strong enough and wide enough to withstand the impact of the falling water.

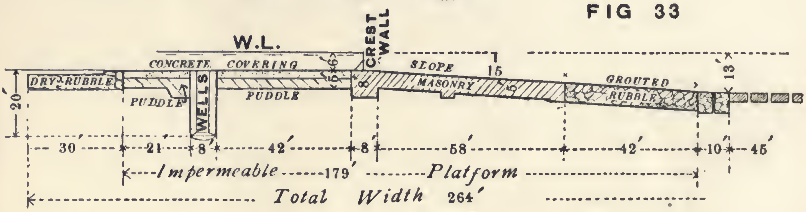
The case of the Narora weir has been examined at length, as it exemplifies the principles on which the designs of recent constructions have been based. There will be the less to say about the other varieties of weirs.

The Chenab weir (Fig. 33), which has been selected as an example of class (2) (no drop, sloping impervious floor), has a

similar history to the Narora weir. But it failed from "piping," or leakage under the floor, and not from the hydrostatic pressure of the percolation water. As originally built, there was only a triangle of stone pitching with a base of 24 feet up stream of the main weir wall. Since the failure an apron of surface-protected clay puddle has been added up stream of the weir wall, as in the case of the Narora weir. It is doubtful whether the addition of a line of piles or wells to the clay apron is a proceeding to be recommended. Certainly,

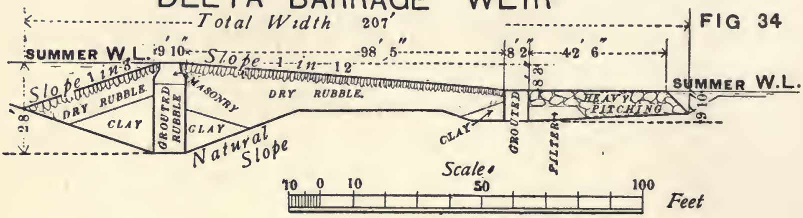
CHENAB WEIR

FIG 33



DELTA BARRAGE WEIR

FIG 34

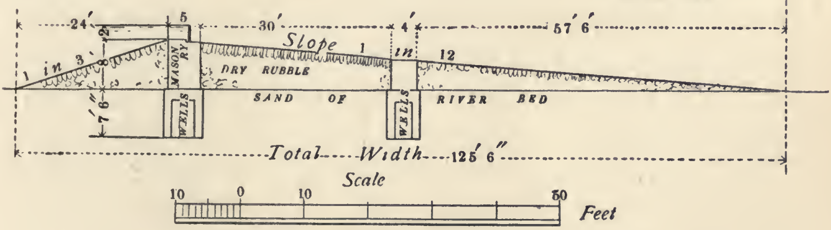


if they form deep *water-tight* curtains, they are more effective in preventing "piping" than a corresponding length of horizontal apron would be, as they alter the direction of the flow and check the movement of the sand. But if the intervals between piles or wells are not perfectly filled and rendered water-tight, they do more harm than good, as the unfilled intervals form vertical runs by which deep springs from the river bed find a free passage upwards to the under-side of the floor. The subject of wells and piles will be further discussed in the next chapter when considering the different methods of constructing sub-aqueous foundations.

The third class of weirs, of which the Sone weir is selected as an example, has no impervious floor, but is made of two (sometimes three) parallel walls, generally founded on wells sunk in the river bed. The spaces between the walls are filled with rubble pitching, with a carefully packed surface of large stones on end. The pitching is continued beyond the lower wall. The cross-section (Fig. 35) gives the design and dimensions of the Sone weir. In the case of this weir, 10 feet is the total head. This is equally divided between the two walls, if both are water-tight.

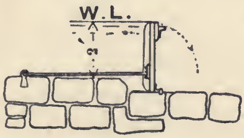
SONE WEIR

FIG 35



CREST SHUTTERS

FIG 36



The Okla weir is remarkable for being constructed on the surface of the river bed without any foundations below that level. There are three walls. The maximum head on the weir is 13 feet. The main wall holds up 4 feet, the middle wall 4 feet 3 inches, and the lowest wall 4 feet 9 inches; that is, supposing that the river below is dry and that all the walls are water-tight. The percolation along the river bed, under each wall, keeps the interspaces full of water, and so causes a division of the head between the walls.

The Sone weir was the type of anicut which influenced the design of the Delta barrage weir in Egypt. The cross-section

given of the latter (Fig. 34) is sufficient to show the design without explanation. The manner of building this weir will be described in the next chapter. It was important that the weir should be made as water-tight as possible in order that there might be no loss in summer when the water was standing level with the weir crest. Mr. R. B. Buckley, who is an authority on these matters and knows both the Sone and Egyptian weirs, has stated in a discussion comparing the two weirs that, "while the Sone weir fulfilled its purpose absolutely, it was not water-tight," and added, "The subsidiary weirs on the Nile were the most water-tight weirs that had ever been built."[1] The core wall, with its up-stream clay weighted with rubble, forms a perfectly water-tight bar across the river. The utility of the down-stream clay is doubtful, but, compressed as it is by a great depth of rubble, it may help to preserve a tight joint with the river bed. At any rate, it removes the point where percolation can first escape upwards to some distance from the core wall. The footing wall is also given a water-tight joint with the bed by means of up-stream clay, so that the maximum head on the core wall is limited to the difference in level between the crests of the two walls. The weir holds up altogether about 10 feet. Probably it could do more if required, as it is considered by some to be abnormally strong.

The heavy blocks of the weir tail are intended to stop cutting back towards the footing wall. Should any holes be scoured out along the down-stream margin, the blocks would subside into them and check the action sufficiently to carry the work safely through the flood. Before the next flood the holes would be filled up with additional stone, and this process repeated from year to year till a condition of absolute stability was reached.

There is one other feature about this Egyptian weir design which is worth attention. Down stream of the footing wall is an arrangement known as "Beresford's filter," so named

[1] Proceedings Inst. C.E., Vol. CLVIII., Part IV.

because Mr. J. S. Beresford, C.I.E., was the first to suggest its adoption in India. It is an inverted filter with strata of materials of gradually increasing size, commencing with quite small stone at the bottom. The filter allows the filtration water to pass freely, but prevents the passage of sand. The percolation water that travels under the work thus issues harmlessly. As a matter of fact, the dry rubble mass between the two walls also acts as a filter bed, as the little percolation water that at times flows over the footing wall has been observed to be absolutely clear.

There are no under-sluices associated with the Egyptian weir, but a lock only for navigation. Neither has it any crest shutters. The afflux in a high flood is almost imperceptible.

On the Indian weirs the crest shutters take various forms, and much ingenuity has been expended on their designs. They are for the most part raised by hand and secured in a vertical position by tie-rods fastened to the crest of the weir. During the flood they are laid flat on the weir crest in recesses made to receive them, so that the flood has a free passage. The shutters of some designs are self-acting, and fall flat when the flood reaches a certain level. Fig. 36 shows the pattern of crest shutters erected on the Sone weir. The under-sluices have also furnished a fruitful field for inventive minds. There are in use many interesting contrivances for rapid opening when the flood comes, some of which have been proved by actual practice to be serviceable. One of the most fascinating arrangements, designed by Mr. Fouracres, has been fitted to the under-sluices of the Sone weir. But though this and others work well, the tendency of evolution in irrigation methods of regulation is the reverse of that which prevails in the animal world. Complexity of structure is giving way to simplicity of design, as being less subject to derangement and more reliable. The system which now finds favour is that of wide vents, fitted with gates which are lifted vertically by an overhead traveller running on rails laid along girders supported on the tops of the

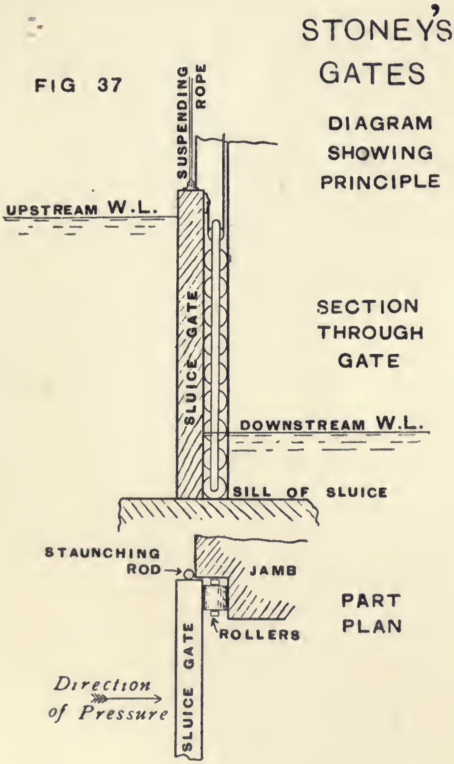
piers above high-water level. The gates, of which there are usually two in each vent, run in cast iron grooves built in the sides of the piers. Friction is reduced by means of rollers, either fixed to the gates or arranged on the "Stoney" system. Hitherto the vents have been generally 20 feet in the clear, though, in Madras, "Smart's shutters" with counter-weights have been erected in all sizes up to 40 feet in length by 12 feet in height. "Stoney's shutters" are now being preferred to "Smart's." Shutters 80 feet broad by 9 feet high, counter-balanced and running in grooves on "Stoney's rollers," are a feature of the design for a proposed regulator across the Penner river in India.

The principle of Stoney's gates is shown in Fig. 37. The gate bears on groups of rollers mounted in hanging frames. The gate moves freely on the rollers, and the rollers on the recessed faces of the jambs, so that friction is minimised. It is easily understood that the sluice gate travels up and down at twice the rate of the roller groups. Therefore, to maintain the correct relative positions of gate and roller frame under all circumstances, the two are connected by means of a wire rope which, passing under a pulley at the upper end of the roller frame, has its two extremities fastened, the one to the upper edge of the gate and the other to a fixed point in the side of the sluice. Thus, as the gate is lifted 2 feet, for example, the roller frame rises 1 foot.

In the various attempts that have been made from time to time to devise a gate that would work with a rolling instead of a sliding contact, the difficulty of obtaining a water-tight closure against the two faces of the sluice has made itself felt. Mr. Stoney has overcome this difficulty in a way that is simplicity itself. In the angle formed by the edge of the sluice gate and the face of the jamb a turned bar, attached loosely to the top of the gate, is allowed to hang freely. The pressure of the water forces this "staunching rod" into the angle against both the sluice gate and the jamb, and a perfectly water-tight joint is

thus secured.[1] The weight of the gate is sometimes balanced by a counter-weight to increase the facility of moving it; but, whether counter-weights are provided or not, the gates are manipulated with the greatest ease.

The system of vertically lifted gates sliding in groves was

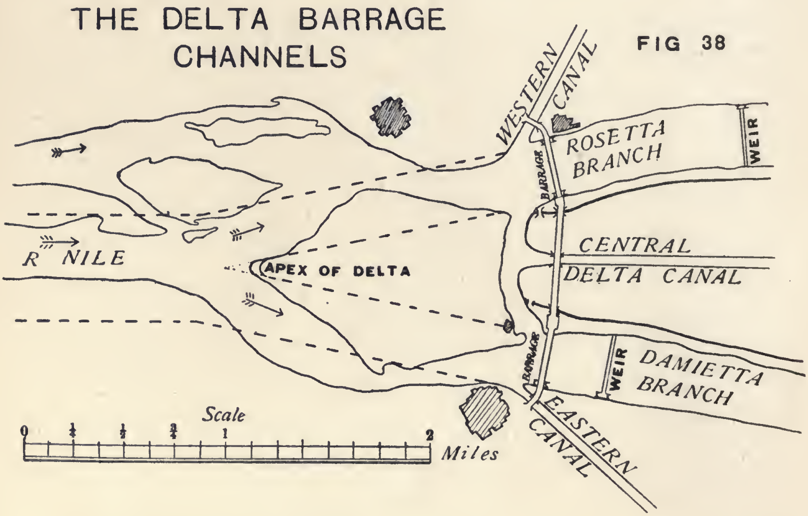


introduced into Egypt by Lieut.-Col. J. H. Western, C.M.G., when he was charged by the Egyptian Government with the restoration of the Delta barrage. In this work the vents are 5 metres (16 feet 5 inches) wide. The same system has been imitated in the newly constructed barrages of Egypt at Assiout and Zifta. This type of river regulator, which

[1] "The Stoney Patent Sluice," by Ransomes and Rapier.

has been classified above as the Egyptian type, will now be described.

The Delta barrage is the prototype of the Nile regulators. It is made up of two separate works, one on either branch of the river close below its point of bifurcation. The main canals, which distribute water to the Delta, take off from the pool above the twin regulators. Fig. 38 shows in plan the general arrangement of these works, and Plate VI. gives a general view



of the down-stream face of the regulator across the head of the Rosetta branch. The Delta barrage[1] has a history of much interest to irrigation engineers. Its construction was commenced in 1843 by M. Mougel, its French designer, when Mehemet Ali was the ruler of Egypt. The design to which it was built is shown in Fig. 39. When the work was subjected to a small head in 1863 and 1867, unmistakable signs of failure appeared in the form of cracks and displacements, and the barrage was forthwith put upon the sick list. The failure

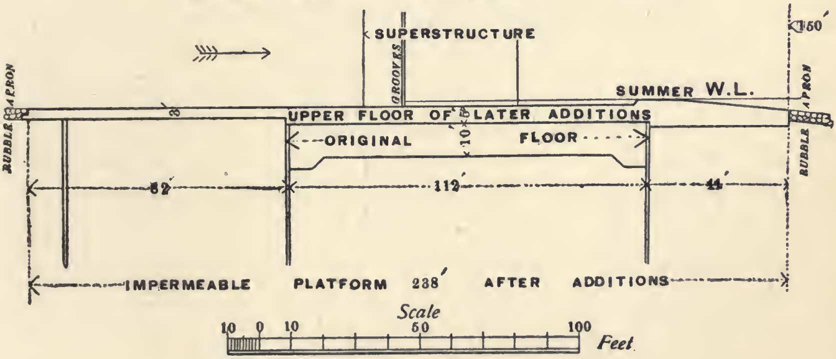
[1] "The Delta Barrage of Lower Egypt," by Major R. H. Brown. Published by the Egyptian Government.

THE DELTA BARRAGE, EGYPT.

was due to "piping." Runs below the floor were developed under the influence of the head of water, and the sand of the foundation bed was carried away by the flowing water till the floor lost its support and settled down. The defects arose, not so much from faulty design, as from careless construction of the foundations. Worried by the impatience and impetuosity of the Viceroy, Mougel Bey's workmen laid the foundation concrete in running water, which carried away the mortar and

DELTA BARRAGE FIG 39

CROSS SECTION OF MASONRY FLOOR



left loose stone, without any binding material, through which the springs of the river bed had free passage. The design, if faithfully executed, was not much at fault. The floor was amply strong to resist the upward pressure due to the head, but its breadth was perhaps deficient; and the protection given both on the upper and lower sides of the flooring was inadequate. From 1867 to 1883 the barrage attracted attention by reason only of its imposing superstructure, but it failed to produce any impression by its performances, for it was weakest where strength was most needed. In 1883 the Director-General of Irrigation proposed to maintain the barrage as a simple bridge, and to provide for the irrigation of Lower Egypt by a system of pumping stations. But in this year Egyptian

irrigation came under the control of Anglo-Indian reformers, and the result, so far as the barrage was concerned, was to save it from rejection, and to raise it to be the head of the corner in the building up of a restored scheme of Egyptian irrigation.

The principle on which the design of the Delta barrage restoration was based was the same as that which was followed in the case of the Narora and Chenab weirs already described. The path of travel for the percolating water was lengthened by the addition of impermeable aprons of masonry up and down stream, thereby increasing the width of floor from 34 metres (111 feet) to $72\frac{1}{2}$ metres (238 feet), two-thirds of the increased width being up stream.

But, besides adding to the width, it was necessary to lay a sound water-tight surface over the old floor, which was cracked and pierced by springs in many places and was otherwise defective. The new covering was made of Portland cement concrete 1·25 metres (4 feet) thick, over which was laid a heavy pavement of dressed Trieste ashlar stone under the arches and over that part of the down-stream apron where the action was most severe. In Plate VI. will be seen where the new floor covering was raised above the general level along the length that was found most defective. A row of piles was added under the up-stream apron—an addition which is now considered a mistake. After the completion of these works, when the barrage was holding up water, springs appeared down stream of a certain length of the floor. The line up stream along which the sources of these springs lay was detected, and the flow stopped by dredging out a shallow trench along the upper edge of the up-stream floor extension and forming a clay apron in it under water, the clay being consolidated by a submerged sledge and protected from scour by a surface layer of cement concrete in sacks.

By means of this restoration work the barrage was made capable of holding up a head of 4 metres (13 feet), as was originally intended, and the consequent effect on the produce of Lower Egypt was eminently satisfactory.

In the next chapter it will be told how the foundations of the barrage were further consolidated by means of cement grout. After this last operation the maximum head held up was 4·35 metres (14 feet). While subject to this head the barrage showed no signs of being unduly strained.

But, though the barrage had now been made to do no more than its duty, it was thought unwise to subject a work of such vital importance to as much even as 4 metres head, if there was a practicable way of avoiding it. So supplementary weirs were proposed to take some of the strain off the barrage. At first no more than this was suggested, but the project grew during the period of study beyond the original idea, and was eventually so expanded that, instead of the associated barrage and weir holding up 4 metres (13 feet) between them, the combination was designed to hold up 6·20 metres (20 feet), the old work being allotted 3 metres of this head instead of its original 4 metres. In this way a more perfect control over the distribution of water at the apex of the Delta has been obtained, not only in summer, but also in flood; while at the same time greater security has been gained. The design of the weir, being of the Indian type, has already been discussed (Fig. 34). The effect produced on the river levels, and the distribution of the head between the barrage and its weirs, are shown in the diagram (Fig. 40). The photograph, of which Plate VI. is the reproduction, was taken before the construction of the weirs, when the barrage was holding up 13 feet head of water. The action of the weirs now ponds up water over the barrage floor so that the talus stones are never visible. On the Rosetta branch of the Nile the subsidiary weir is 1,500 metres (1,640 yards), and on the Damietta branch 500 metres (550 yards), down stream of the barrage, so that the weirs are entirely separate works from the older construction.

Other instances of the Egyptian type of regulator have been lately built at Assiout, in Upper Egypt, and at Zifta, in Lower Egypt. As the design of the latter is practically the same as the

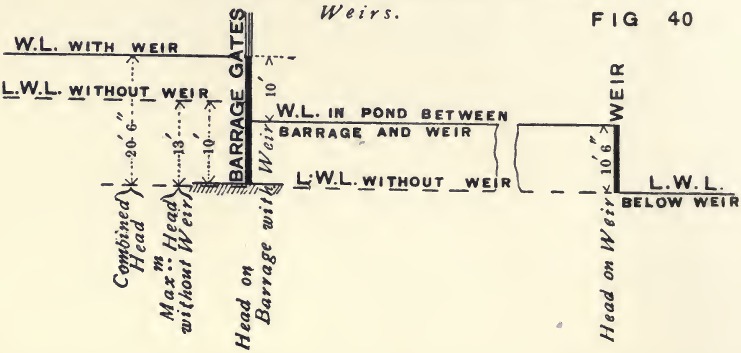
Assiout barrage design, but modified in certain details as a result of the experience gained in building the Upper Egypt work, the cross section of the Zifta barrage is selected as an example of the most recent form of the Egyptian type of river regulator. Fig. 41 gives the principal dimensions. It will be observed that the floor has a diminished thickness down stream of the piers, as the hydraulic pressure upwards, due to percolation, decreases towards the down-stream end of the floor, and the floor surface beyond the piers is not subject to the pounding of water falling over the gates. The clay apron up stream,

DIAGRAM

OF WATER LEVELS AT THE DELTA BARRAGE

before and after construction of the Weirs.

FIG 40



weighted with rubble, forms an extension of the impermeable floor, and removes the starting-point of the flow of the percolation water to the up-stream edge of the clay. Down stream of the floor is an inverted filter bed overlaid with the heavy rubble of the talus. Up-stream and down-stream rows of piles, with joints grouted up solid with cement, form continuous curtains. The up-stream piles are useful in increasing the distance the water has to travel, after starting from the up-stream edge of the clay apron, before it presses upwards on the under side of the floor. The down-stream piles are not necessary to the finished work, but they facilitated the laying of the concrete

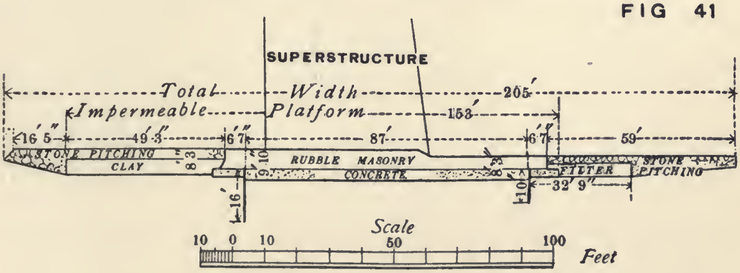
platform, and were also a security against the material of the river bed below the concrete being withdrawn by springs flowing from under it to the pumps which kept the water down during the construction of the floor. The down-stream row of piles was therefore retained, but was made of less depth than the up-stream line.

It was found during the construction of the Assiout barrage that the weak point was the line of junction between piles and concrete, along which springs forced their way upwards. In the Zifta barrage design the masonry floor was therefore extended outwards for a short distance up stream and down

ZIFTA BARRAGE

CROSS SECTION OF FLOOR

FIG 41



stream, to cover the heads of the piles, an arrangement which would enable the springs to be dealt with and effectually closed if they appeared.

The Zifta barrage was designed to hold up 4 metres (13 feet) of water, which it proved, after construction, to be fully capable of doing. But before it had been in use two years, the advantage of holding up more than 4 metres (13 feet) was recognised, and a subsidiary weir has been constructed down stream to enable the heading up to be increased. This weir is a more modest one than the Delta barrage weirs, but it is of much the same design to a smaller scale.

With reference to the question of the future type of river

regulator that engineers in India may be expected to adopt, the following passage occurs in a Manual on Irrigation Works, compiled by Mr. B. P. Reynolds, Instructor in Civil Engineering, for the use of the students at the College of Engineering in Madras, India. The manual is dated January, 1906, and therefore may be assumed to be giving expression to the recent thought of engineers in India, so far as the author of the manual was acquainted with it:—"There can be no doubt that the weirs of the future will be of the open type, raised little, if any, above the bed of the stream and fitted with movable shutters on the crest; and since it is necessary that some kind of bridge should be erected over them from which to work the lifting gear of the shutters, it follows that these weirs practically become regulators. In almost every case, except perhaps for very broad rivers, the shutters will be of the lifting type; falling shutters, while useful for broad rivers, have the serious objection that once they fall the flood water must drop nearly or quite to the level of the floor of the weir before they can be raised again, while with lifting shutters the water can be held up to any convenient height and all excess safely passed." The Zifta barrage is an embodiment of modern ideas as to the principles on which a river regulator should be designed, and it would appear from the passage quoted above that the Indian type is likely to be modified in such a way that it may eventually differ by little, if at all, from the Egyptian type. The existing barrages of Egypt are divided into bays of 5 metres (16 feet 4 inches) width, and have their floor surfaces flush with the bed of the river. With the facility of regulation provided by Stoney's shutters the width of the bays could without inconvenience be increased four or five times, as in the regulator across the Penner river; and, if ample width of waterway were allowed, there would be no objection to raising the floor a little above the river bed with the object of decreasing the height of shutter required to hold up water to the desired level. Mr. Buckley ("Irrigation Works in India," p. 149) describes

the method of remodelling the Coleroon anicut in India. The original weir proved in time to be not high enough. A new "anicut" was therefore built, up stream of the old one, with fifty-five 40 feet spans, regulated by lift shutters 4 feet high. As the sill of the new "anicut" is 4 feet below the crest of the old weir, the top of the shutters is only 2 feet higher than the crest, and therefore, if the sluices in the old weir were to be wholly closed, the new work would have only a 2 feet head to support, while the old work would hold up 4 to 5 feet. This combined work has, therefore, a resemblance to the Egyptian Delta barrage and its weirs, but the order of construction of barrage and weir was reversed. The new "anicut" of the Coleroon combination is in fact, as Mr. Buckley states, "an arched bridge, the water passing through it being regulated by means of lift shutters." In other words, it is a river regulator of the same type as the barrages of Egypt.

Reference has been made in the earlier part of this chapter to the intention of the Egyptian Government in 1883 to adopt pumping from the river as its only method of supplying Nile water for irrigation. For some years previously pumping stations at Atfeh and Khatatbeh, in Lower Egypt, had been at work lifting water from the Rosetta branch of the river for the irrigation of the Western Province of the Delta. A contract had been concluded with a company for the working of these stations, the terms of which were modified in 1883 to provide for an increase in the amount of water delivered into the canals by the pumping stations. The new terms provided for a supply of 2,000,000 cubic metres a day (818 cubic feet a second) at Atfeh, and 2,500,000 cubic metres a day (1,022 cubic feet a second) at Khatatbeh, at an annual cost of about £50,000. This contract was to last till 1915. As the Delta barrage stood condemned as incompetent to serve the needs of irrigation, it was proposed to extend the same system of supply by pumping to the whole of Lower Egypt at an initial cost of £700,000 and an annual expenditure of £250,000. But fortunately for Egypt,

before a decision had been taken regarding this proposal, Colonel (now Sir Colin) Scott-Moncrieff was entrusted with the management of the irrigation of Egypt. He pigeon-holed the pumping project, declared himself in favour of a restored barrage, and forthwith took steps that led to its successful restoration.

The total cost of the restoration was £475,000. About £500,000 more was spent on the east and west main canals to fit them for their work. It may be stated in round figures that the barrage restoration project cost one million, and, as the pumping project was estimated to cost £700,000, its actual cost would probably have been also about one million. But when a comparison is made of the annual expenditure in each case, the difference is striking. The Delta barrage costs less than £10,000 a year to maintain and regulate, and without any further expense is capable of distributing any increased supply that may be provided to meet the demands of a growing area of cultivation; whereas the annual cost of lifting the water by pumps —estimated at £250,000 in 1883, before the development in cultivation of the past twenty years had taken place—would increase with the quantity of water to be lifted, and fluctuate with the price of coal. Moreover, it would be a risky thing for Egypt, whose coal supply must come by sea, to be dependent on imported fuel. In time of war the coal supply might be cut off, and a coal famine, of two months duration only, would, under such circumstances, be enough to seal the fate of the growing cotton crop, worth £15,000,000 at present prices. The barrage is undoubtedly the most reliable agent for Egypt to entrust with her interests. It has, since its restoration, become so efficient, and is so unmistakably the proper instrument for the water distribution of the Delta, that the Khatatbeh pumping station has been dismantled, and its engines and pumps transferred to another station which provides for the drainage of low-lying lands in the north-west portion of the Delta. The Atfeh pumping station is still maintained, as it is so situated

that it can assist in supplementing the summer supply by pumping into the Mahmudia Canal the water that comes from springs and percolation in the river trough itself, between the barrage and Atfeh, when the Delta barrage is closed. This source of supply has not been mentioned in Chapter IV. as it is peculiar to Egypt, but, as similar conditions may arise elsewhere, it may be worth while to point out the measures taken in Egypt to utilise every available drop of river water in its irrigation. By the time that the river discharge reaching the Delta barrage has so far decreased that it is no more than that required by the canals fed from the river above, the gradual lowering of the barrage gates is complete. The leaks round the ends and between the gates are then caulked with rags, and the closure of the two branches of the river by the barrage made practically water-tight. But below the barrage there are, on each branch, some 200 kilometres (125 miles) of channel from the beds and sides of which spring and percolation water collects in quantity not to be despised. When the river discharge is due to this source alone, the salt water of the Mediterranean invades the lower reaches of the river branches and, mixing with the spring water, renders it unfit for irrigation purposes. Therefore, in order to make this spring water available for irrigation, the engineers have, since the barrage became efficient, adopted the practice of constructing temporary dams, one in either branch some little distance from the point where it joins the sea, with the double object of excluding the salt water and of retaining the spring water. On the Damietta branch this water is drawn upon by a number of privately owned pumps, and on the Rosetta branch by a few private pumps and by the Government pumps at Atfeh. More than half of the supply, however, flows by gravitation into canals irrigating low-level lands in the north of the Delta. The quantity of water obtained during the summer by such means from the Rosetta branch is generally about 100,000,000 cubic metres, though as much as 170,000,000 is reckoned to have

been obtained. The Damietta branch is calculated to similarly supply 80,000,000 cubic metres.

The Atfeh pumping station is the only remaining Government station in Egypt which is worked in the interests of irrigation. Its performances are, moreover, limited to lifting from 70,000,000 to 75,000,000 cubic metres during the summer when the want of water is most felt.

But, though the irrigation of the Delta can be more economically and efficiently done by a system of canals depending on barrages than by pumping, there are certain isolated areas in Upper Egypt which cannot be given perennial irrigation without pumping. The Egyptian Government has now decided to erect pumping stations for East Giza, a tract of country comprising about 38,000 acres lying immediately to the south of Cairo. As this land cannot be served by a perennial canal on account of its isolation, there is no choice in the matter if it is to be given perennial irrigation.

In Upper Egypt there are some 200 pumps operated under private enterprise by engines of an aggregate horse-power of about 5,000. The largest among these are worked in combination with sugar factories, for the irrigation chiefly of sugar cane. During the flood season they are relieved by the inundation canals whenever these latter flow at a sufficiently high level to give irrigation by "free-flow." The following are the five most powerful stations.

Names of Stations.	Horse-power.	Area of Crop Irrigated.
Mataana	150	1,500 acres
Armant	250	2,500 ,,
Dabaya	150	1,500 ,,
Naga Hamadi . .	500	5,000 ,,
Ayat	400	4,000 ,,

The lift in summer in Upper Egypt is from 8 to 10 metres (26 to 33 feet), and the price of coal about £2 a ton.

There is an interesting venture, lately undertaken by a company, to irrigate the Komombos plain in Upper Egypt.

The soil of the plain is derived from the high ranges which skirt the Red Sea, and is expected to be productive when irrigated. But its surface is some 20 metres (65 feet) above the summer level of the Nile, and half that height above high-flood level. At this remote point coal may be expected to cost £2 10s. a ton. There are no local supplies of fuel, as the plain is bare. Nevertheless a company has applied for and obtained a concession for the reclamation of the plain. Three pumps of 1,300 horse-power are to lift water about 24 metres (78 feet) for the irrigation of 20,000 acres. To adapt the pumps to the varying conditions of river level in flood and summer they have been sunk in a pit about 5 metres (16 feet) below the level of high flood. The success of this undertaking depends upon the efficiency of the pumps and good management, for the conditions are formidable.

Sir William Willcocks in "Egyptian Irrigation" estimates the number of pumps driven by steam power in Lower Egypt at 3,777, with an aggregate horse-power[1] of 36,000. This estimate probably includes the pumps used for drainage purposes, which will be referred to later.

It is rather a remarkable fact that in India, hitherto, not an acre of land has been irrigated by Government otherwise than by natural flow. In so large a country, where all sorts of conditions exist, there must be land so situated with reference to water supply that pumping must be the most convenient, if not the only possible, way of irrigating it. At length the Madras Government has recognised this in a particular instance, and has approved a project known as the "Divi Pumping Project," which provides for lifting water 10 to 12 feet for the irrigation of 50,000 acres. The pumping station will consist of eight 160-B. horse-power Diesel oil engines and Gwynne centrifugal pumps with discharge pipes 39 inches in diameter.

The cost of lifting a given quantity of water varies naturally

[1] The horse-power given is the nominal horse-power of commerce, equal approximately to half the indicated horse-power.

with the height it is raised and with the price of fuel. It also varies with the power of the pumping stations, large installations working more economically than small ones. The question of cost will be examined when pumping stations for drainage purposes are under consideration.

CHAPTER VII.

METHODS OF CONSTRUCTION.

UNDER the head of Construction the irrigation engineer has to deal with works as big as the Assuan dam and as small as a field outlet of a few inches diameter. Between these extremes lie anicuts, barrages, canal head works, weirs, regulators, locks, inlets, escapes, syphons, aqueducts and culverts. The common characteristic of all such works is that they have to control the flow of water in one sense or another, and therefore should be built of materials that will resist the action of water. Otherwise the ordinary principles of construction apply to them. Good stone and brick in hydraulic mortar are the most reliable materials. Iron can be safely used under water only on surfaces, and for those structural parts which can be periodically examined, so that any deterioration may be detected and made good. Wood is only fit for use in temporary works and for movable parts such as regulating apparatus. Some hydraulic engineers of a robust faith may be found to put their trust in ferro-concrete, or *ciment-armè;* but they would do well to remember that the process is too new for time to have concluded its course of object-lessons. Those who are interested in seeing what daring flights of design the advocates of this system are capable of making should turn to p. 4 of Willcocks' "The Nile Reservoir Dam at Assuan and After."

In the figures illustrating the text the different descriptions of masonry employed in any work, selected as an example, are not distinguished one from another, as the choice of material depends generally on local resources. In Chapter VI., p. 116, ashlar was mentioned as a good covering for floors which are

subjected to the impact of falling water, with the proviso, however, that the ashlar must be properly bedded. In Mr. Buckley's account of the failure of the Narora weir, quoted on p. 118, it is stated that a strong spring passed under the stone flooring and lifted it bodily over a length of 340 feet. Now this could not have happened if the ashlar had been properly bedded. There must have been unfilled spaces between the ashlar covering and the floor below it, over which the water pressure acted. Assuming that the vertical joints of the ashlar were perfectly filled, and that the bed joints were imperfectly filled, and also that the sub-ashlar spaces were in communication with the up-stream head of water by ever so small a channel, the ashlar would be in danger of being lifted if the void spaces and head of water were great enough to develop the pressure necessary to overcome the weight of the stone. Supposing this were so and the ashlar blown up, the remaining thickness of floor, below the ashlar, might then be too weak to resist the upward pressure of percolation water from below, and a failure of the work would result by the rupture of the floor. In consequence of this objection to ashlar, namely, the difficulty of securing a perfectly uninterrupted bond between the ashlar and the masonry below it, it is sometimes considered preferable to dispense with an ashlar covering and to build the floor of homogeneous material. The floors of both the Assiout and Zifta barrages in Egypt were so built, the material of the floor above the bed layer of concrete being of rubble stone in 3 to 1 cement mortar throughout. All the stones were laid, as far as possible, with their longest dimensions vertical, so as to obtain a vertical bond. The masonry was brought up rough to floor level, and was surfaced by laying fine concrete (2 stone, 1 sand, 1 cement) between the projecting points of the rubble masonry. All points of stones that projected above the correct floor-surface level were dressed off with a stone-dresser's hammer.

So far as the foundations of most of the larger works are concerned, the methods of execution are those which are imposed by

the necessity of building below the level of lowest water. The nature of the foundation bed, and the strength of the springs over the foundation area, are important matters for consideration in selecting the method to be adopted. But the price of materials and facilities for obtaining them, as also the quality of the labour market and the nature of engineering plant available, have to be taken into account. In the case of works to be built on rivers which are in flood during certain months of the year, or in countries where a rainy season interferes with construction, the duration of the working season also will influence the decision as to the most convenient method to adopt.

If the springs of the foundation bed are not expected to be too powerful to be dealt with by the pumps which can be brought to site, the ordinary method of getting in foundations below spring level is to surround the area of operations by banks so as to exclude the outside water (if the foundation pit is not otherwise enclosed), and to get rid of the inside water by pumping. It may sound a simple matter to surround the area by banks capable of excluding the outside water, but in some cases this operation is a very formidable one, on the success of which the whole work depends. The enclosing banks should be made well clear of the outside limits of the foundation area, with a good margin to spare to allow for the earthwork settling down to a broader base under the action of percolation, which will increase as the inside water is lowered by pumping. Interior space is also useful as affording room for stacking materials, and for the erection of pumps with their wells. The wells for pumps should be outside the extreme limits of the permanent work. The pumps keep the water level in the enclosed area low while the excavation of the foundation pit is carried down to full level and the masonry of the foundation is laid, so to speak, in the dry. As the bed on which the bottom concrete is laid is often covered with several inches of water, wherever springs are numerous, a liberal allowance of cement must be used in mixing the concrete.

One advantage of this method over others is that all the work done is in sight at the time of execution, and it can therefore be supervised the more efficiently. But it has this disadvantage, namely, that, unless the springs are intelligently and skilfully treated, defects in the foundations will be created by the water forcing its way either under or through the masonry. It happens sometimes that the supervising staff has not the experience necessary for successfully dealing with the springs, but gains it as the work proceeds, so that the first season's work is not without its mistakes. The golden rule to be observed in dealing with springs is that no attempt should be made to stop them working until they have been surrounded on all sides by masonry of sufficient strength to resist their efforts to find a new outlet under or through it. In the case of any work of similar design to that of the Zifta barrage (Fig. 41), if the cement concrete, which forms the bottom layer of the foundation platform, is advanced from one extremity of the work in an even line towards the other, regardless of what springs it may meet with, the springs will form runs for themselves through the unset edge of the concrete layer. And, as the work advances, more and more springs will assert themselves in the same way, until there is a strong out-flow along the advancing edge of the concrete, due to the combined action of all the springs encountered; except such as may have forced their way side-ways to the lateral margins of the concrete layer and have found for themselves a free outlet there. The cementing material of the concrete will thus be washed away as soon as it is laid, and runs will be formed under and through the foundation platform, which will be sources of trouble afterwards. The way to avoid this is carefully to locate all springs in advance of the work, and to carry the concrete round them, but not over them. Thus the springs will continue to work unmolested. But, in order to prevent the discharge from them interfering with the progress of the work elsewhere, their water must be confined and led

away in pipes or channels of set masonry over or through the concrete layer, and be allowed to flow until the sources are completely surrounded by masonry too strong for the springs to burst through. They can then be forcibly stopped with safety, and be rendered powerless to work harm. The methods of dealing with springs vary in detail with the ingenuity of those in charge of the work, but the guiding principle is the same in all cases, namely, to offer no violence to the spring till sufficient forces are marshalled and the investment is so complete as to make any attempt to break out hopeless and submission inevitable.

The method of enclosing the foundation area and keeping the inside water down by pumping was recently adopted in Egypt for the construction of the Assiout and Zifta barrages, as it was also some years previously for the restoration works of the Delta barrage.

The Delta barrage restoration, carried out under the direction of Col. J. H. Western, C.M.G., was a work of much difficulty. The barrage, as has been already stated, consists of two regulators, one across the head of each of the two branches into which the Nile divides at the apex of the Delta. The regulator across the Rosetta branch has sixty-one openings of 5 metres (16 feet 5 inches) and two locks, and is 465 metres (1,525 feet) long between the flanks. The regulator across the Damietta branch had originally seventy-one openings and two locks (reduced during the restoration to sixty-one arches and one lock), and was 535 metres (1,755 feet) long. To carry out the restoration work it was necessary to enclose half of one regulator at a time, leaving the waterway of the other half unobstructed to pass the river discharge; so that the work had to be spread over four seasons. The working season between two successive floods extended from November to June. Four months of this time were occupied in making the enclosing banks and in pumping out and clearing the area of work. At one point the enclosing bank had to be made in a maximum depth of water of 15 metres (49 feet). When the pumping had lowered the

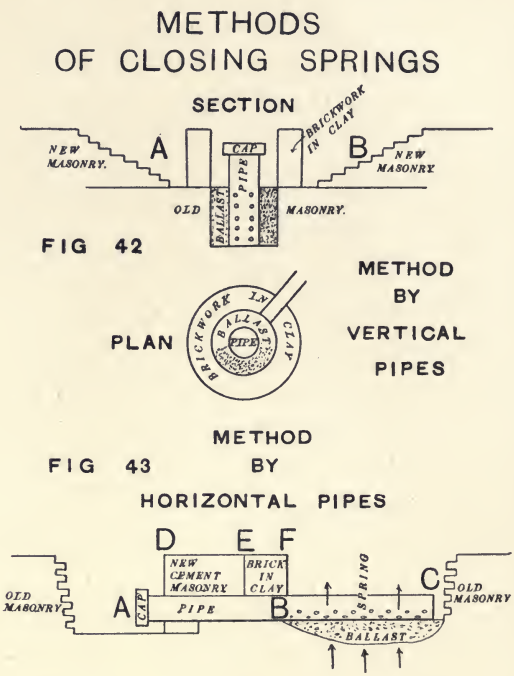
inside water sufficiently to allow of the masonry work being carried on, the head of water against the up-stream bank was 5·25 metres (17 feet). As the river bed was sand, so great a head naturally gave rise to strong springs inside the enclosure, not only outside the limits of the barrage platforms, but also, in consequence of original defects in construction, through cracks and runs in the floor itself. In one instance a crack had opened out into a fissure 4 inches wide for a length of about 13 feet. According to the report of the resident engineer, Mr. A. G. Reid, "where cracks of this sort occurred they were staunched as follows: the broken floor was cleared of *débris* bit by bit and covered at once with sand to a depth sufficient to keep down the springs. It was then surrounded at a distance by concrete laid after thorough clearing on the sound floor and carried up to a level at which the springs could not break through it. The concrete was then pushed on inwards until it was stopped by the flow of water. When this occurred the sand was carried away as deep as possible, and rubble masonry laid in cement mortar was built on the sand, a trench about 5 metres wide being left coinciding with the crack in the floor. Concrete metal was laid a few inches deep, and on it a pipe 2 metres longer than the crack, closed at one end and perforated with half-inch holes along its under half-circumference for so much of its length as coincided with the crack, was securely built into the new masonry for its imperforate length. An outflow drain was left in the masonry in the prolongation of the pipe, and the water from the broken floor was thus passed through the pipe to the pumps. When the masonry had set, the pipe was covered in with masonry laid in cement gauged neat, and the whole then raised to a safe height. The end of the pipe was afterwards closed with an iron plate and the outflow channel built up."

The manner of dealing with the springs met with in the worst opening of all, where it was found necessary to build the new floor, overlying the old, with a surface some 3 metres

(10 feet) higher than that of the original floor, is thus described in the same report: "The springs under this arch were numerous and prevented the water being got down below 2 metres above floor. They were closed by the aid of iron pipes. The floor having been cleared of *débris*, silt and rubbish as far as possible, ordinary cast iron pump pipes, 6 feet long, were put into place, one vertically over each spring, and concrete was tipped to water surface round them and over the whole area of the floor. Whilst this was being done, the water coming through the pipes was led away to the pumps in troughs and by channels previously prepared. When the concrete had set for six days, a trench 1 metre wide and extending from pier to pier was dug through the concrete down to floor level, a site having been chosen which was, as far as could be judged, sound. The floor was thoroughly cleansed, and the trench was then filled in with concrete laid in layers and rammed. The object of this was to make a water-tight diaphragm extend from the old to the new floor, and thus to prevent creep of water between the two. The pipes were then filled with finely broken concrete metal and closed by quarter-inch iron plates bolted on to their flanges, indiarubber packing rings being used to make the joint tight. The whole floor was then concreted over to the necessary height and the ashlar face laid."

But the greatest source of trouble were the numerous springs which found their way upwards between the piles of the original rows of piling within which the floor had been built. Each separate jet had to be led into a pipe of suitable size surrounded with masonry, and the pipe closed and built over after the masonry had set. As the manner of dealing with springs is of such importance, the soundness of foundations depending on their successful treatment, Sir William Willcocks' description of the means adopted to imprison the springs along the old sheet piling of the barrage is worth quoting ("Egyptian Irrigation"). See Figs. 42 and 43.

"1. *Vertical Pipes.*—The spring was dug out to a depth of, say 30 centimetres below the surface of the old masonry, and a vertical tube of from 5 to 10 or 15 centimetres diameter, according to the quantity of the water, was inserted. The hole was then filled up with ballast round the tube. This tube was drilled with holes on the lower half of its length, while at the upper end were cut the threads of a screw, so that a cap might



eventually be screwed on. Round the pipe, and removed about 10 centimetres from it, a ring of brickwork in stiff clay was built, open on one side; the cement masonry was then brought up from A and B till it was flush with the brickwork in stiff clay, and was allowed time to set. When set, the brickwork in clay was removed, and the space between the pipe and the cement masonry was filled up with cement mortar, or concrete or brickwork, an open space being still left on one side to allow

the water coming up through the ballast to flow freely away. When the cement mortar had thoroughly set, and was strong enough to prevent springs working up through it, the opening was quickly shut up with dry cement and cement mortar, and weighed down, and the water began to flow freely through the top of the pipe. When the cement closing the opening had thoroughly set, the cap was screwed on the pipe and the whole built over.

"2. *Horizontal Pipes.*—The pipe in this case was drilled with holes on half the circumference of half the length, *i.e.*, on a quarter of its surface, and was laid horizontally in a trench, with the holes over the spring, which had already had ballast strewn over it. The ballast was spread round half the pipe to the axis B C. At E F a ring of brick in stiff clay was built round the pipe, and at D E cement masonry round the pipe. When the masonry at D E had set thoroughly, the brickwork in clay was removed and replaced by cement mortar or brick-work, while the space from B to C was covered with cement mortar and masonry, and the water allowed to flow down the pipe C B A. Great care had to be taken that a hand pump kept the water at M always lower than the top of the pipe, until the masonry above B C had thoroughly set. When the masonry had set the cap A was screwed on, and the whole space carefully built over in cement masonry."

The Assiout barrage, in Upper Egypt, spans the undivided river as a regulator with 111 openings of 5 metres (16 feet 5 inches) each and a lock, making up a total length between abutment faces of 820 metres (2,690 feet). The laying of the foundations was complete in three working seasons, a different section of the work being enclosed each season, while the river discharge was allowed to pass in the other sections. The maximum height of the enclosing bank was 9·8 metres (32 feet 2 inches). The head of water against it, when the inside water had been pumped down to the required level,

varied from 4·70 metres (15 feet 5 inches) to 6·25 metres (20 feet 6 inches). The bed of the river was sand, and the whole foundation bed was alive with springs. The most suitable pumps for unwatering the foundations were 12-inch direct acting centrifugals; larger pumps were found unwieldy, and smaller pumps, though useful for small areas on account of their portability, proved unsuitable for use as main pumps. At one time there were seventeen 12-inch, two 10-inch, six 8-inch, and three 6-inch centrifugal pumps at work. The main pumps were mounted in pairs on circular brick wells, 5 feet in diameter, sunk to a suitable depth just outside the line of the pitching, and sealed at the bottom with concrete plugs. Apertures to admit the water to the wells were made in their sides at successively lower levels as the water level in the foundation pit was reduced.[1]

The springs were dealt with in various ways, in accordance with the principles laid down above. But the final closing of the pipes, to which the springs had been confined, was not done as at the Delta barrage. Provision was made for screwing on other pipe lengths to a height of 5½ metres (18 feet) above the floor, so that, when the masonry had set, each spring might be forced backwards by a column of cement grout, and any run or cavity created by the flow of the spring be filled by the grout. As the springs were so numerous, causing an outflow at the advancing edge of the concrete, it was frequently necessary to stop any further advance and to recommence the work at a fresh point some distance ahead, whence the concrete was carried back to meet the arrested portion. Large openings were temporarily left along the line of meeting as vent-holes for the springs, which were then controlled and finally extinguished by the employment of perforated pipes and cement grout under pressure.

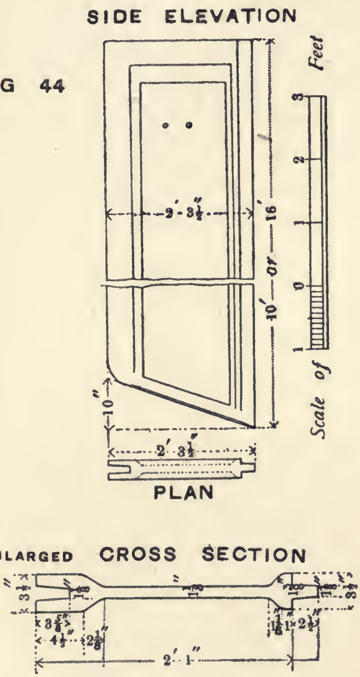
It is now recognised that the use of sheet-piling of the ordinary

[1] "The Barrage across the Nile at Asyût," by G. H. Stephens. Proceedings Inst.C.E., Vol. CLVIII., 1904.

description to form curtains is a mistake, as experience gained at the Delta barrage and elsewhere has taught that the unfilled joints form so many leads to bring deep-seated springs to foundation level, while, in consequence of these joints, the advantage of a continuous deep curtain wall is lost. To obviate these objections a special form of pile, which provided for the complete

CAST IRON PILES

FIG 44



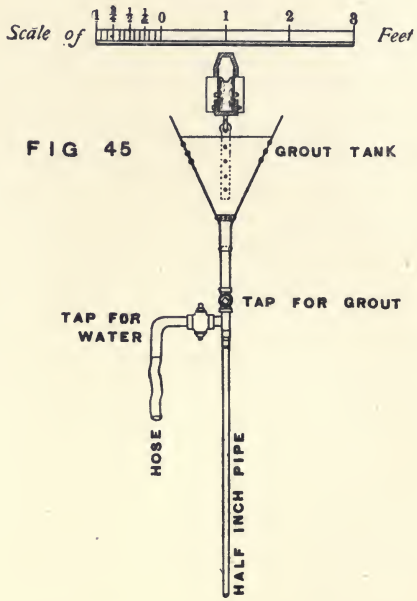
filling of the joints with impervious material, was adopted at Assiout and Zifta. This pile was of cast iron, with a tongue and groove arrangement by which one pile locked with another. The groove was deeper than the length of the tongue, so that, when two piles were locked together, there remained a space between the end of the tongue and the back of the groove, into which a small tube could be inserted (Fig. 44). After the piles

were driven and the pile-driver had advanced to a safe distance, a tube was introduced into the groove space and water turned on under a head. The jet of water cleared out the sand in the joint, and, as it did so, the nozzle of the tube descended to the bottom of the joint. The water was then turned off and cement grout substituted (Fig. 45). The tube, with its nozzle,

GROUTING APPARATUS

FOR PILE JOINTS

FIG 45



was then gradually lifted out of the joint, leaving it full from top to bottom of cement grout, which in a few hours set hard enough to resist the strongest spring. In this way a continuous curtain, without open joints, was obtained along the line of piles.

The piles were driven as soon as the excavation was sufficiently advanced for the pile-drivers to get to work, so that the piling was complete before the bottom layer of the excavation was cleared.

The disadvantages of putting in foundations with strong springs in action over the foundation bed have caused other methods to be resorted to. The system which makes use of compressed air is well suited to subaqueous work in which depth of foundation, but not continuity, is required. The sinking of cylinders, for instance, to act as foundations for the girder supports of river bridges is frequently effected by this method. But it is not so conveniently applied to the construction of works which have to withstand a head of water and require continuous foundations of unvarying depth without intervals. Moreover, the system requires special plant of a somewhat complicated order, and trained labour skilled in the process, as there is much danger attending its employment by untrained hands.

In India the method of getting in foundations by well-sinking is in favour, and has been repeatedly employed with much success. Where a curtain wall has to be formed in sand or silt below spring level, it is most unwise to attempt to get it in by lowering the water by pumping below the general foundation level. Well-sinking is one method of avoiding the necessity of doing so. A group of wells is also often sunk to provide extra support for heavy lock walls, piers, or other parts of the superstructure requiring greater depth of foundation than is given to the lighter portions of the work. Well-sinking may be carried out with the help of compressed air, but it is usually done by excavating the sand or soil from the interior by ordinary dredging plant. Wells may be circular or rectangular. Curbs with sloping under-sides and outside cutting edge are first bedded in the sand or soil at the natural water level, or at the level to which it may be judged convenient to lower the water by pumping. The wells are built on the curbs, and the masonry given time to set. They are then weighted, and the sand dredged from within by special plant, so that the wells gradually sink below water level as the excavation continues. More height is added to them (if not

originally built to full height), and the sinking is continued till the bottom of the well has reached the required depth. Cement concrete is then lowered to the bottom of the well, and a plug of 4 or 5 feet thickness formed; or the plug may be made by cement grouting if the water in the well is allowed to stand at spring level while the grouting is being done. When the plug has had time to set the interior water is pumped out, and the well filled with ordinary concrete, or even simple sand, as the interior core does no work. The intervals between wells are then cleared out as far as possible and filled with concrete. The superstructure is afterwards built on a platform covering the wells.

In the construction of the Sone weir in India, for example, well-sinking was extensively used for the foundations of the weir walls and under-sluices. The under-sluice piers and the entire floor of the under-sluices (which is 537 feet by 123 feet in area) are founded on rectangular blocks or wells, generally 8 feet square, which are sunk all over the area to a depth of about 8 feet; the blocks under the piers are longer and deeper. The wells are filled with concrete and covered with masonry topped with ashlar 18 inches thick (Buckley).

An excellent example of the use of wells for foundations is furnished by the new Nadrai aqueduct in India (see Fig. 60, Chapter IX.). The piers which carry the aqueduct are founded on wells sunk 52 feet below the bed of the lower channel. For such foundations as these well-sinking is a most useful and efficient system.

The sinking of foundation wells is sometimes a troublesome and tedious operation, especially if the supervising staff and the labour employed have not acquired skill by previous experience. What to do, and what not to do, to ensure that the wells may sink vertically and uniformly, is only to be learnt by actual practice.

The great objection to the use of wells for the foundations of a weir core wall, or for a curtain wall of a work which is

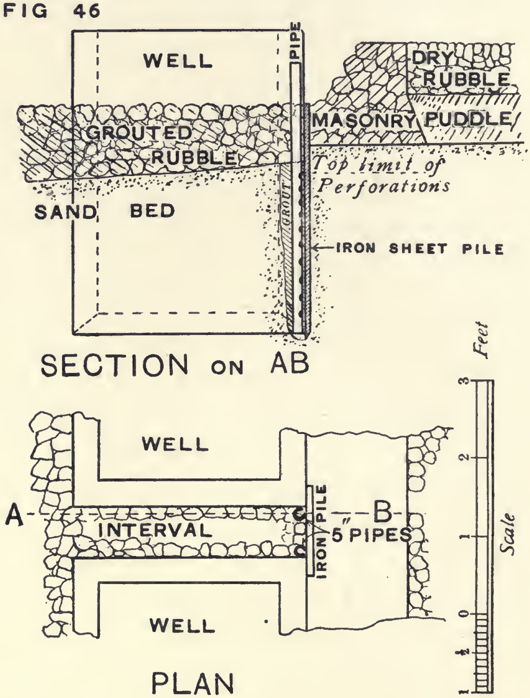
subjected to a head of water, is the difficulty of filling the intervals between wells so thoroughly that they may be water-tight. The filling seldom reaches to the full depth of the wells, and if the wells should have sunk out of plumb, as they often do, the clearing of the interspaces, and therefore the rendering of them water-tight, becomes almost an impossibility. For this reason cast-iron piling with grouted joints was preferred to a line of wells for the curtains of the Assiout and Zifta barrages, and not for this reason only, but also because the piling can be executed expeditiously, and the well-sinking cannot. Time is required to construct the wells, to allow for the masonry setting, to sink the wells, and to close the intervals before the concrete of the floor can be commenced. With cast-iron piling it can be arranged that the piles shall be at site before the excavation is ready for them, and that they shall be driven in advance of the final clearing of the foundation bed, without causing any delay in the commencement of the laying of the concrete.

Wells were recently used in Egypt to form an up-stream curtain wall to a new head built to the canal which takes off from the Nile at Cairo and flows to Ismailia, carrying the water supply of Suez and Port Said. The foundations of this work were as treacherous as they could be, and, as the new work was to replace two others that had successively failed, it was highly desirable that there should not be a third failure. The curtain line of wells was sunk 5·75 metres (19 feet) below floor surface, or canal bed level. To get the full benefit of this depth of curtain, it was necessary to arrange for a water-tight closure of the intervals between the wells to their full depth. Piles, made of half-inch steel plate stiffened with T irons, were driven outside the wells to close the intervals (see Fig. 46). These piles, though flexible to a certain extent, could not be expected to lie so close against the masonry of the wells as to produce a water-tight joint. So, in order to staunch the joints between the piles and the wells, a pair of pipes was sunk in the

well intervals, one pipe lying in each of the angles formed by the pile and the faces of two adjoining wells. The length of pipe below the floor foundation level was perforated, and the pipe was so placed that the perforations faced the angle between pile and well. The pipes were sunk by means of a jet of water playing on the sand at the foot of the pipe from inside the pipe

WELL INTERVALS SHUBRA

FIG 46



itself. When sunk to the required depth, the pipes were filled with sand to ensure the exclusion of cement grout when grouting the floor. In that operation (which will be described later) the cement grout encircling the pipes made a water-tight joint with the piles and wall of masonry outside the piles, so that the well intervals were made absolutely water-tight from the bottom to the top of the grouted floor, above which it was of

course easy to build them up solid. There remained the depth of interval below the grouted floor to render water-tight. After the foundation pit had been laid dry by pumping, subsequent to the operation of grouting the floor, the staunching pipes were cleared of sand by means of a jet of water, and were then filled with grout after the manner of grouting up the joints of the cast-iron piles before described. It was found in every case that the two pipes of a pair were in communication below the grouted platform in which their upper ends were embedded, as the grout, poured down one pipe, was observed to rise in the other. The fact observed, namely, that these pipes were in communication with each other under the grouted floor, makes it almost certain that the arrangement has secured a continuous water-tight curtain wall down to the bottom of the wells along the whole of the up-stream edge of the floor.

There is yet another method of getting in foundations below water. Cement, used in the form of grout, for binding together materials under water, had been used successfully in breakwaters and other constructions by different engineers before the system received its most notable application in the construction of the subsidiary weirs below the Delta barrage of Egypt. In discussing this method it will be convenient to describe first the practice as exemplified in the building of these weirs, and to state afterwards what principles must be followed. The object of the weirs has been already explained in the preceding chapter, and the design is given in Fig. 34. The core and footing walls up to the natural level of the water in the river during the working season, and also the foundation of the locks associated with the weirs, were formed under water by the cement grout system. The manner of proceeding was as follows :—

The river level in the branch selected for the season's work was lowered as much as possible by shutting down the gates of the Delta barrage up stream of the weir site, and thus diverting all the river discharge into the other branch. A trench was then

dredged across the river bed to dimensions and levels corresponding with the foundation bed of the weir and its lock, as shown on the designs to which the work was to be built. Along this trench the two walls of the weir were formed of a continuous succession of blocks from one side of the river to the other by means of bottomless boxes put together in the dredged trench with the help of floating plant (Fig. 47).

The boxes, being formed, were lined with sacking by the help

APPARATUS FOR FORMING GROUTED BLOCKS

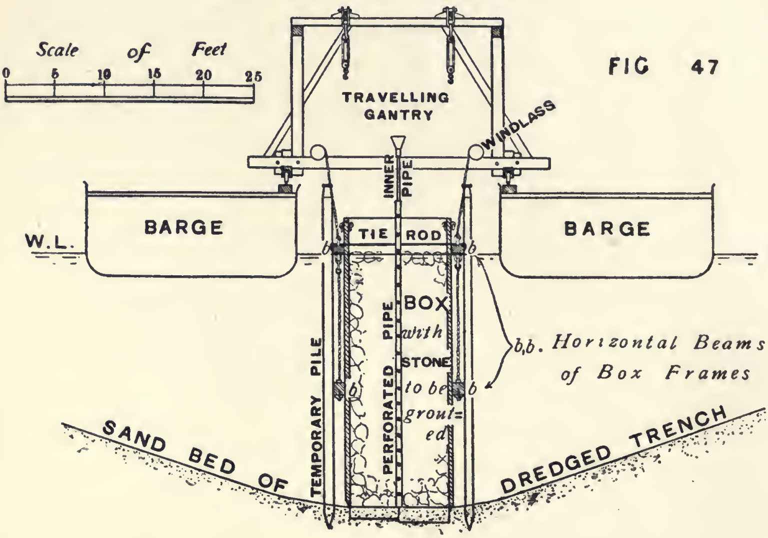


FIG 47

of divers, in order to make them cement grout-tight, though not water-tight. Four perforated pipes were next fixed vertically at equal intervals along the centre of the box. This done, the boxes were filled up to a little above water level with rubble of all sizes that a man could carry, and unperforated pipes were inserted into two of the perforated pipes, reaching almost to the bed of the river which formed the bottom of the box. Funnels having been fixed at the top of these inner pipes, cement grout was poured down them. Above each of the other two alternate

pipes was arranged a stand carrying a simple grooved wheel, over which a string ran, having at one extremity a ball so weighted that it sank in water and floated in the cement grout at the bottom of the perforated pipe, and at the other extremity a small weight just heavy enough to keep the string taut. As the grout rose in the box the float in the pipe rose with it, and the small weight, moving in correspondence down a scale fixed to the stand, registered the amount of rise. When the grout had risen 2 or 3 feet the inner pipes and recording stands changed places, and grout was poured down the second pair of pipes till the gauges over the other pair recorded a further rise of 2 or 3 feet; whereupon inner pipes and recorders changed places again, and so on till the grout had mounted to the top of the stones, displacing all the water in the box. As the sea of grout rose from below, the inner pipes were gradually shortened by successively unscrewing the short lengths of which they were made up. The object of this was that the fresh grout, being delivered just below the surface of the rising grout, might not disturb the lower layers and interfere with the process of setting. Cement grout is twice as heavy as water; consequently the grout, if delivered below the water, would remain there, and would displace the water simply by its gradual rise from below. To permit of the ready escape of the water, vents were made in the sides of the boxes just above the level of the water outside.

If the cement grout had been poured directly into the perforated pipes, each bucket of grout would have had to fall through water, and have at least suffered in quality, if it had not been altogether "killed" by excess of water. By using an inner unperforated pipe, with its lower end just below the surface of the rising sea of liquid cement, a continuous column of grout was added to the previous mass without any further admixture of water. This is an important point to pay attention to if this method of construction is imitated elsewhere. Another important condition is that the grout must be of neat

cement, without the addition of sand or other foreign material; for if a mixture is made of substances of different specific gravities, the constituents will, in the liquid form of grout, separate from each other under the action of gravity, and form distinct strata before the setting properties of the cement have had time to prevent the segregation.

As soon as the cement grout had risen in the box high enough to envelop the top stones, or slightly higher than the water outside the box in the river, the scum was cleared off, small stone was bedded in the surface grout, and the box and its contents left alone till the following morning, when it was found that the block had set sufficiently to stand by itself. The parts of the box containing it were then cast loose and moved forward to form the next block, and so on across the river. Work was started on the core wall foundations at several points along the line simultaneously by the different rafts fitted up for the purpose. At each point of starting the first box formed was four-sided. On the completion of the first block one end of the box was removed, and the next and subsequent boxes were made with the three remaining sides, the block last formed closing the fourth side. The upper part of the core wall above water level was then built in the dry, and the clay, rubble, and apron blocks put in place.

Plate VII. shows the west weir under construction. The wall on the left is the lower part of the core wall which was formed by grouting, the water level having sunk since the near blocks were made. The wall on the right, appearing just above water level, is the footing wall. The near cross-wall is a connecting wall which, in its finished state, will form a toe to support the shore abutment slopes; the farther cross-wall, of which the closing block is being formed, is the first of four made at intervals of 100 metres to divide the weir into compartments. Beyond that is an interval through which the reduced discharge of the river is allowed to pass. On the far side of the river the floating plant is at work forming the blocks of the

THE WEST WEIR OF THE DELTA BARRAGE UNDER CONSTRUCTION.

distant lengths of the two walls, which will later on be connected across the central channel with the walls on the near side. The depth of water against the core wall at the time of taking the photograph was 20 feet, and against the footing wall 10 feet.

The dimensions of each block made along the core wall trench were 10 metres long by 3 metres broad and 7½ to 6 metres high (32 feet 9 inches by 9 feet 10 inches by 24 feet 7 inches to 19 feet 8 inches); that is, each block was about half the size of a two-storeyed cottage. These blocks were formed wholly under water.

The proportion of cement to the quantity of masonry formed by this method is 37 per cent., a high figure for concrete; but the rapidity and certainty with which the work can be executed produce economies under other heads of expenditure, and the results obtained are so perfect as to justify the employment of this system, even if it be comparatively costly, wherever perfection in the quality of the work and rapidity of construction are desired.

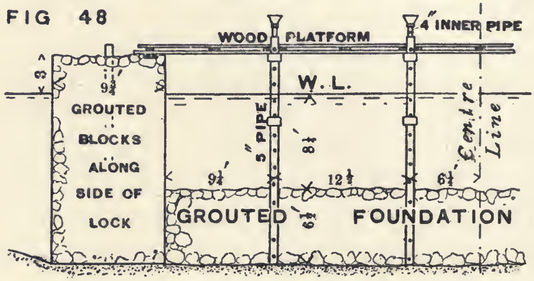
As the method of cement grouting was adopted for getting in the sub-aqueous portions of the weir proper, so as to avoid the difficulties and disadvantages of dealing with springs which are encountered when the method of unwatering the foundations is resorted to, it seemed desirable and consistent to apply the same method to the lock foundations, an undertaking which had never been attempted before. The floor surface of the finished lock would be below the low water level of the river, so that the grouting of the foundation could not be continued till the grout rose to water surface, as in the case of the core wall blocks, but had to be arrested when the grout had risen to a level 2½ metres (about 8 feet) below the water surface. The manner of execution was as follows: The foundation bed was first dredged out to the necessary level, which was 4½ metres (say 15 feet) below low water level. Two parallel walls (see Fig. 48), bounding all the lock area on either side, were then formed by

the same system as that adopted for the foundations of the core wall, and with the same plant. The rectangle of which these walls formed the sides (100 metres by 17 metres, or 328 feet by 56 feet, in the clear between the walls) was then closed at the two ends by sheet piles supported by horizontal beams which were kept in place by piles driven a short

GROUTING METHOD OF GETTING IN FOUNDATIONS

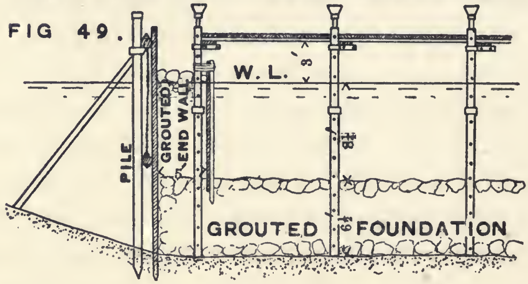
HALF CROSS SECTION OF LOCK

FIG 48



SECTION OF ONE END WALL

FIG 49.



distance into the bed of the river and tied at their tops to the side walls already made (see Fig. 49). A staging was then constructed across the enclosed space from side wall to side wall, the perforated pipes having been first fixed in place about $3\frac{1}{4}$ metres ($10\frac{1}{2}$ feet) apart all over the area. The pipes were fitted with iron brackets to make them serve as upright supports for the staging. Two metres depth of rubble, concrete

metal and pebbles were then thrown in to form the floor foundation. At about 1 metre distance from the two ends of the lock area a second interior line of sheet piling had been arranged with its lower end below the level to which the 2-metre layer of rubble would come (Fig. 49). All the sheet piling was lined on the inside with sacking to prevent the escape of cement grout between the joints, in the same way as in the boxes. When the 2-metre depth of floor material had been deposited, as ascertained by sounding rods, grouting commenced at one end of the lock and continued till the other end was reached, the level to which the grout rose being noted by the float and gauge arrangement as used on the boxes. When the 2-metre layer had been given time enough to set, the end spaces were filled up with stone and grouted. After three days' interval the enclosed space was pumped out, and the grouting was found to have formed a perfectly sound floor without the sign of a spring in it. The rest of the lock floor and walls was built in the dry in the ordinary way after clearing and cleaning the surface of the grouted platform.

The advantages of this system of cement grouting are that the springs never get a chance of troubling, and the sub-aqueous work constructed by its employment is perfect in quality and of a strength more than sufficient. No expensive plant is required and no skilled labour, except only a few carpenters and mechanics to prepare the parts of which the boxes are formed, and a few intelligent supervisors to direct the putting of them together. The system has also the merit of rapidity of construction. The objection to it is its costliness, though much of the expenditure in cement is balanced by economy in staff and in all the extra outlay which accompanies a prolongation of the period of construction.

The use of cement grout for the construction of the Delta barrage weirs was preceded by a remarkable operation on the Delta barrage itself carried out with the help of cement grout, in imitation of similar work done some years previously

at the Hermitage Breakwater, Jersey, by the late Mr. W. R. Kinipple. It will be remembered that the bottom layer of the concrete platform on which the barrage rests had its cementing material washed away during construction by springs, leaving loose concrete metal behind. This defective layer, and the original unsound floor above it, was covered over and cut off from communication with the river water by Colonel Western's enveloping additions to the floor. But the loose material still remained, affording a passage of practically no resistance to the travel of the percolation water along that length of its path which followed the under-side of the original foundations. It was felt that, if this bottom stratum of the old floor could be made impermeable, additional security would be obtained. The introduction of cement grout under pressure to the bottom layer, with the view of filling the interstices of the concrete metal with set cement, was the method selected. The accompanying diagrams (Fig. 50) will help to make the following description of the process intelligible.

Holes were first bored as shown by the strong black lines, and cleared to at least 1 metre below the lowest level of the foundations. Cement grout was then poured into each bore, and the pouring continued until the grout filled the bore to the level of the roadway or pier tops. When the bore was full, the pressure exerted by the column of cement at the bottom of the bore was, in the case of the bores made from roadway level, 26 tons per square metre (2·4 tons per square foot), and, in the case of the two others, 19 tons per square metre (1·76 tons per square foot). So great a pressure was sufficient to force the cement into all cavities in communication with the bore, so that the grout must first have enveloped all loose material, and then, by its property of setting, have compacted it into a solid mass. That the cement did not fail to set was sufficiently proved, as in several instances it was brought up in a hard state when clearing the adjacent bore to which it had travelled below the floor.

In consequence of the success obtained at the Delta barrage, cement grout was employed to overcome difficulties of construction in other troublesome works which the irrigation officers of Egypt had to execute. One of these it may be of advantage to instance as affording an example of the combination of the two

DELTA BARRAGE
BORES FOR GROUTING

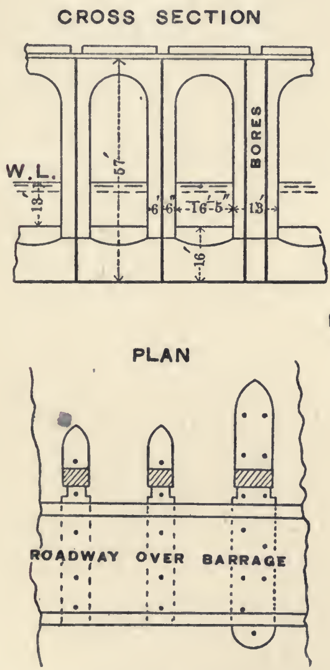


FIG 50

systems of well-sinking and cement grouting for getting in foundations below water level. Reference has already been made to the Ismailia Canal head when describing an arrangement for making a water-tight closure in the intervals between wells. On account of the treacherous nature of the subsoil which would have to bear the weight of the work, it was decided to sink wells below the general floor foundation level,

with the object of giving increased support to the lock and abutment walls and of providing curtain walls up stream and down stream. By the addition of a few wells elsewhere a continuous boundary of wells was formed enclosing the whole foundation area. These were sunk to the required depth, their tops being then at about the level of the future floor surface. To execute the well-sinking, as well as the necessary preliminary excavations, a bank had to be formed on the Nile side to keep out the river water, and pumps had to be constantly at work to keep the inside water down. The excavation of the foundation pit was carried down by hand as low as possible, which was to a level some 2 metres (6 feet) short of floor foundation level. As at this level strong springs rose over the whole area of the foundations through black sand in a formidable manner, and as previous experience had shown how difficult it was to build sound work on such a substratum of quicksand with springs rising through it everywhere, it was decided to get in the floor platform all over the area bounded by the wells by the cement-grouting method, as was done in the construction of the weir locks of the Delta barrage. The programme which was followed was this: After closing the intervals between the wells by iron piles, the "saddle-back" and rubble pitching up stream of the regulator and lock were completed to the extent shown in Fig. 46. The wing walls were built up over their wells to a considerable height above the finished level of the floor. The river dam was then cut, and the water allowed to rise in the pit and find its own level. A sand dredger was next admitted through the opening in the dam, and the foundations of the floor were dredged out to full depth. The dredger having done its work made its exit, and the cut in the dam was closed again. The grouting pipes and staging were then arranged over the foundation area. As soon as the pipes were in place rubble was thrown in round them to the required height of nearly 2 metres (about 6 feet). Grouting was then carried on after the manner already described, and continued till the floor rubble was grouted

to the top. The work was left undisturbed for three days, after which the pumps were set to work to lower the water in the enclosed foundation pit. When the surface of the grouted platform had been laid dry and cleaned, it was found that the operation had been successful, and that there were no springs left to interfere with the work. The floor was then completed and the superstructure built in the dry.

It is sometimes desired to lay a syphon under a running canal which cannot be closed for a period sufficiently long to allow of its construction in the ordinary manner. The usual method would be to divert the canal into a temporary channel passing outside the syphon site. But there are some situations where a diversion cannot be made except at a prohibitive cost. In such cases some method of laying the syphon under water must be devised. In Egypt several pipe syphons of 5 feet diameter, some of them over 250 feet in length, have been laid in running canals without resorting to the usual method of a diversion. The barrel of the syphon may consist of a pipe of five-sixteenths to half an inch thickness of mild steel plate, stiffened with angle irons and cover plates. The pipe is put together on the canal bank in the neighbourhood of the syphon site. The two ends of the pipe are closed with water-tight doors, and means of admitting water provided. The pipe is then launched and floated into correct position over a trench which has been dredged out across the canal ready to receive it. Temporary banks, made round the outer ends of the dredged trench, connect the extremities of the canal banks which have been cut through to form the trench for the pipe. The pipe is now ready for sinking. It is dangerous to let the water into it and leave it to find its own way to the bottom. It would certainly tilt in doing so, one end sinking and the other rising up out of the water, and the joints would be so strained that a leak would probably be the result. To control the sinking, the pipe should be supported at both ends by ropes manipulated from rafts or boats, and the ropes should be paid out evenly, so that the pipe

may be let down quietly in a horizontal position on to its bed. When the pipe is in place, the canal banks are remade over it in their former alignment, and the ends of the syphon outside the canal banks completed.

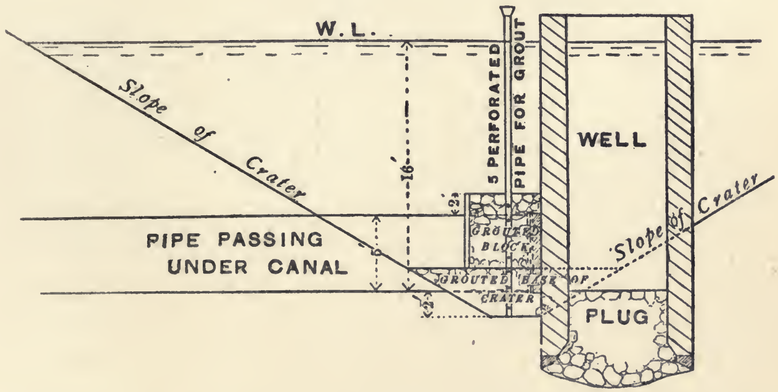
The building of the masonry ends, or the fixing on of the rising terminal pipes, is sometimes a matter of considerable difficulty on account of the proximity of the flowing canal. In the case of a syphon of two pipes of 5 feet diameter laid, by the system just described, under the Ibrahimia Canal, in Upper Egypt, the ends were formed of bent continuations of the horizontal pipes rising to the inlet and outlet levels at either end. After the horizontal lengths had been successfully got into position and the canal banks remade over them, it was found impossible to get rid of the water about the pipe ends so as to admit of the rising lengths being added. So the horizontal lengths were lifted again, the bends and part of the rising ends added above water, and the sinking repeated. In this way the work was successfully completed.

The same difficulty of building the ends of another syphon in Egypt was surmounted in quite a different way. The syphon was a simple pipe of 5 feet diameter with masonry inlet and outlet wells at its extremities. The pipe was got into place successfully, but the endeavour to complete it by building the masonry ends outside the banks was for a long time abortive, on account of the high level water in the canal close alongside and the moving sand below. Eventually a masonry well was sunk as near the end of the pipe as possible (Fig. 51), but there remained an interval of 6 to 8 inches between the two. The pipe end was closed by a wooden door and tarred canvas, kept pressed against the pipe by wedges driven by divers between door and well. A crater was then dredged out with its bottom from 18 inches to 2 feet below the under-side of the pipe. An upright grouting pipe, perforated at its lower end, was fixed as shown in Fig. 51. Rubble was then deposited at the bottom of the crater up to a

third of the pipe's diameter, and the mass grouted up. A box was then formed on the top of the grouted block with the well-face as one side of it, and the box was filled with rubble to a height of 2 feet over the pipe. The contents of the box were then grouted up to the top. After a couple of days the water in the well was pumped out, and a passage cut between the well and pipe to the same diameter as the pipe and in prolongation of it. The collar of grouted rubble was found to have formed a perfectly water-tight joint between the well and the pipe. Both ends of the syphon were treated in the same way.

END OF PIPE-SYPHON

FIG 51



The well walls were then cut down on the outside to the proper levels for the sills, and the slope revetments completed.

The tunnel which is to carry a double line of railway under the Detroit river, between Windsor on the Canadian side and Detroit on the United States side, is to be constructed on somewhat the same system as the syphon just described. The tubes will be floated into place and sunk into a trench dredged out to receive them. But the tunnel will be made up of several tube lengths which will be fastened together under water. It would seem that the ends of the tube lengths will be open in most cases, and that they will not be self-buoyant. The

manner of caulking the joints between two adjacent lengths is thus described in the *Standard* of November 1st, 1906. The passage is quoted here as the device may be found useful in the construction of irrigation syphons. "Each tube when manufactured will be fitted with a sleeve at one end, which can slip over the end of the adjoining tube previously sunk. The sleeve is to be provided with a flange which can be bolted to a corresponding flange of the adjoining tube, a rubber gasket being placed between the two. A similar rubber gasket is to be provided at the inner end of the sleeve, bearing up against the edge of the next tube. In bolting up the flanges, which must be done by divers, the rubber gaskets must be squeezed together between the ends of the tubes to form a tight joint. This space will be filled with a grout of pure cement. The ends of the tubes at the joints are, further, to be fitted with flange angles on the inside for the purpose of caulking between them should the joints be found to leak. In order to enable the contractors to begin lining the tubes before the sections are sunk all the way across the river, some of the tubes may be provided with bulkheads to keep out the water when the tubes laid are being pumped out."

CHAPTER VIII.

MEANS OF DISTRIBUTION.

Canals and Drains.

In Chapter VI. the means of drawing water from the source of supply were considered. In this chapter a description will be given of the means by which the water is carried from the source and distributed to the fields on which artificially irrigated crops are to be raised.

A canal system consists of channels to carry the water, of regulating works (usually of masonry) to control its flow, and of drains to discharge surplus water from the irrigation zone.

The irrigation channels are usually classified under the heads of main canals, branch canals, distributaries, and field channels. Assuming that the position of the offtake has been selected, the main canal, between its head and the point where it first enters the tract to be irrigated, should be carried along the alignment which is economically the most advantageous. The shorter this unprofitable length of canal can be made the better, provided that the selection of a favourable site for the head works is not unduly influenced by the claims of economy to the neglect of more important considerations. Within the area commanded—that is, inside the limits of the land which is to be brought under irrigation—the alignment of the canals must be such as to facilitate direct irrigation from them. If the country is made up of ridges and intervening depressions, the main canal should run along the principal ridge. Its branch canals should follow the subsidiary ridges, and the distributaries the minor ridges, so as always to keep the water at a height which will command the land to be irrigated and

in a position to flow on to the fields, and also to avoid crossing the natural drainage lines of the country. If a contoured map exists, it is more or less a simple matter to lay down upon it the scheme of canals and drains adapted to the natural configuration of the ground. But the configuration may not be one of alternating ridges and depressions. There is need sometimes of designing irrigation systems to serve the flat lands which are found bordering a river that flows along a valley. If the river follows the lowest line of the valley bed, these plains have a surface slope towards it; but if the river occupies a broad valley and has raised the land level alongside it by the deposit of successive floods, the land surface slope falls away from the river, as with the Nile valley in Upper Egypt. In the former case the canal would be aligned along the outer edge of the flat tract at the foot of the rising ground enclosing the valley, and in the latter case along the high margin adjoining the river. The flat lands (*vegas*) of Andalucia, in Spain, bordering the river Guadalquivir, may be taken as an example of lands sloping towards the river. A canal to irrigate them would have to be aligned along the foot of the hills that bound the valley, and would unavoidably cross all the drainage lines leading to the river. At every crossing a passage for the drainage water would have to be provided.

But, whatever may be the nature of the country through which canals are carried, no attempt must be made to prevent the drainage from flowing along the line to which it has established a "right of way," if provision can be made for its unimpeded passage by constructing either a syphon to carry it under the canal at the point of crossing, or some other work serving the same end. It may, however, in some cases, be preferable to divert the drainage and carry it away in a new channel made expressly for it. But, in any case, the universal rule applies that the drainage must not be ignored, and full provision must be made for the disposal of all excess water, whether it be due to rainfall or irrigation.

The principles that govern the alignment of drains are the converse of those applicable to canals. If natural drainage channels do not already exist where drainage is a necessity, artificial drains must be aligned along the lowest lying land, that is, along the bottom of the depressions or valleys between the ridges on which the canals and distributaries run.

The next things to consider are the points which influence the design as regards the longitudinal section of the irrigation and drainage channels. The most important matter affecting the question of the gradient of main canals is silt deposit. Silt is the eroded matter which is brought down in suspension by rivers from their upper reaches. The greater the velocity the more and the heavier is the silt that the water carries along with it. When the river leaves the hills and ceases to be torrential, it drops its heaviest loads of shingle and boulders, but keeps the sand and soft mud for distribution in the plains. Before the river nears the sea it has left behind all but the finest sand and mud which give the richest deposit of all. There is silt which is fertilising, and there is silt which is sterile. The former it is desirable to draw into the canals and carry forward to the fields in abundance; the latter it is better to exclude from the canals altogether, if possible, as being so much "dead weight in the boat." At the same time, it is important that the deposit of silt in the canal itself should be a minimum. As silt deposit takes place wherever there is a change of velocity from a higher to a lower rate, the velocity of flow in the canal which ensures the transport of a maximum amount of silt to the fields with a minimum of deposit on the way, should theoretically be the same as that of the river at the point where the canal takes off from it. But it is rarely, if ever, possible to carry this theory into practice, for not only does the river velocity vary at different seasons, but it is sometimes so high that, if the canal were to flow at the same rate, its water surface slope would be steeper than the slope of the country, and the water would never come to land

surface. Consequently it is found more practicable to make the rate of river-flow past the offtake approximate to that of the canal than to make the canal agree with the river. This is brought about by working the gates of the under-sluices in the river weir or regulator, and the shutters of the canal head, in such a way as to discourage as far as possible strong currents and eddies in the neighbourhood of the head sluice, and to produce comparatively still water at the canal offtake. The coarser and heavier silt is carried along by the lower water in contact with the bed of the river, and it is this material that it is desirable to exclude from the canal, for these two reasons, namely, that, if admitted, it is sure to cause troublesome deposit in the first reaches of the canal; and, even supposing some of it succeeded in reaching the fields, it would not be welcomed there, for it would have taken the place of the lighter and more fertilising silt which is so valuable to farmers. To prevent the admission of this heavy and infertile matter, it is necessary to draw in the upper water from the river and to exclude the lower. This is sometimes effected by giving the canal a head sluice of considerable length and a raised sill, and by working the shutters in such a way that the top layer only of the river water may be drawn into the canal. But this method of drawing off from the river, and of reducing the rate of flow past the canal head by closing the adjacent under-sluices, will cause some of the excluded silt to be deposited in front of the head sluice and above the under-sluices. This must be got rid of by periodically opening the under-sluices, so as to create a sufficiently high velocity to scour away the deposit. While this operation is being carried out, the canal head should be temporarily closed. In this way, by an intelligent management of the regulating gates of the under-sluices and of the canal head, the silt difficulty, which has troubled every irrigation engineer, may be at least partially overcome. The head sluice must therefore be so designed that water may be admitted to the canal in accordance with these

principles, which have been deduced from the teachings of experience, chiefly in India (Buckley, Chapter III.).

It is not, then, the river velocity that determines the velocity of flow that is to be adopted for the canal, but other considerations. If the canal is to be navigable, it is desirable that the velocity should be as low as is consistent with its more important duty of irrigation, the avoidance of silt deposit, and a reasonable regard for economy. The lower the velocity of flow the larger the cross-section must be to carry the required discharge, and consequently the greater the cost of making the canal. If the velocity is too low, silt deposits in the canal, the discharging capacity of the canal is diminished, and much expense is incurred in clearing out the deposit. If the velocity is too great, the reverse takes place; the bed is scoured out, the banks are undermined and slide forward, and the channel soon becomes irregular. Neglecting the needs of navigation, the ideal velocity is that which will neither create scour nor encourage deposit, but will enable the water to carry forward the silt which comes into the canal from the river, and keep it in suspension until the field, which is to be irrigated, is finally reached. There both the water and its silt will find useful work to do. What this ideal velocity should be varies with the quality and quantity of the silt that the river carries in suspension, and with the nature of the soil forming the bed and banks of the canal.

In India Mr. R. G. Kennedy has attempted to determine this point. He selected for his observations certain canals in which the flowing water carried a constant percentage of silt in suspension. The cross-sections and velocities at thirty sites, where no silting or scouring took place, were measured, and it was found that at all these sites the following equation expressed very approximately the invariable relation between the mean velocity and the depth of the water:—

$$V = c\,d^m = 0{\cdot}84\,d^{0{\cdot}64}$$

Thus the higher the velocity the greater would be the correct

depth, and *vice versâ.* Therefore it follows that, for a given discharge, canals with a high velocity should be comparatively narrow and deep, and those with a low velocity wide and shallow. On different canal systems the values of c and m in the above formula might be expected to vary slightly. It would appear that Mr. Kennedy's conclusions require further testing before they can be confidently accepted as the expression of prevailing law.

It is chiefly the flood conditions that have to be taken into account in determining the figure to adopt for the velocity of flow in the canal. During the season of low discharge the river carries little or no silt; in flood it is carrying its maximum. In Indian rivers during flood, the proportion by weight of solid matter to liquid may be as great as 1 to 30. It frequently happens that the conditions are such that silt is deposited in the canals during flood, and picked up and carried away by the clearer water that enters after flood, even though the velocity in the latter case may be lower. This is due to the fact that, in flood, the water admitted brings in more silt from the river than the canal velocity enables the water to keep in suspension; whereas, after the flood, the clearer water is not carrying all it can, and so picks up some of the lighter silt as it goes along. Mr. Buckley instances the case of the Sirhind Canal in India, on which careful observations of silt deposit have been made. In August and September the velocities observed were 3·2 and 3·0 feet per second respectively, and with these velocities silt was deposited: in October and November the velocities were 3·5 and 3·3 feet, and the quantity of silt that was removed in these two months was more than double the quantity that had been deposited in the two preceding months. In the two later months, when scouring replaced deposition of silt, the velocity of current was only slightly increased, but the flowing water was clearer. From experiments made during the flood season in Lower Egypt, Sir William Willcocks came to the conclusion that, in canals with their heads suitably

placed, a mean velocity of from ·70 to 1·00 metre (2·30 to 3·28 feet) per second is sufficient to prevent any appreciable deposit, but that deposit takes place with mean velocities of ·60 metre (2 feet) a second and under. In Lower Egypt the silt carried by the river is very fine.

It may be stated, as a conclusion based on experience in India and Egypt, that a velocity of from 2 to 3 feet a second is required to carry forward ordinary silt, the required velocity being greater or less according as the matter in suspension is coarse or fine, and the water heavily or lightly charged with silt.

The velocity of flow depends on the surface slope of the water in the canal. In the first reach of the main canal, between its head and the upper limit of the land commanded by the canal water, the water surface slope must be steep enough to produce a velocity that will decidedly discourage silt deposit. But, provided this condition is fulfilled, it is advantageous to have a surface slope of low gradient, as the flatter the slope is, the shorter will be the length of canal required to bring the water to country surface. Within the commanded area the surface slope of the canal is determined, in most cases, by the slope of the land. If, however, the land surface is so steep that a water surface slope which conforms to it gives an inconveniently high velocity in the canal, the canal must be divided up into reaches with a suitable gradient, produced by impounding the water at regulating falls situated at the lower end of each reach.

The velocity of flow and water surface slope having been determined from the foregoing considerations, there remains to be calculated the discharge the canals will have to carry. The data for this calculation are the area of crop to be irrigated and the accepted "duty" of water for the period of maximum demand. In India the *kharif* season and in Egypt the flood season are the periods in which the canals have, in most cases, to carry the greatest discharges. Mr. Buckley states

that, "as a general rule, main canals irrigating *khareef* (or monsoon) crops should be capable of carrying a maximum discharge of 1 cubic foot per second for every fifty acres of that crop which it is intended to irrigate, and they should be capable of carrying 1 cubic foot for each 100 acres of *rabi* (cold weather) crops. The extent of land which can be irrigated may be determined either by the quantity of water available in the source of supply or, when the quantity is abundant, by the area which can be commanded by the system."

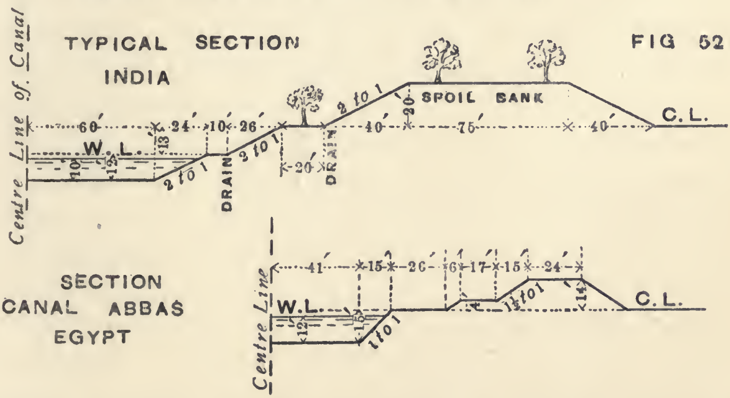
In Egypt, during the Nile flood, the supply is abundant and sufficient for the area commanded. The whole of the perennially irrigated tracts are commanded by the canal systems of Egypt, and so the area commanded becomes identical with the gross area. The discharge which the canals have to carry in flood to serve this area is calculated at the rate of 25 cubic metres an acre. This is equivalent to an allowance of 1 cubic foot a second for every ninety-eight acres. The area under rice in Egypt is insignificant as compared with the total area under irrigation during the flood season; otherwise it would have to be separately allowed for in the estimate at double the general rate. Nevertheless it is as well to add a small percentage to the total to provide for the rice crop, and also for the washing of salted lands which is carried on when water is plentiful. The allowance in Egypt may therefore be taken to be rather more than the *rabi* allowance of India of 1 cubic foot a second for every 100 acres.

The velocity of flow and the maximum discharge are the factors with which the calculations of the dimensions of a canal are made. Its cross-section must come under consideration at this stage. A theoretically perfect cross-section for a large canal demands a depth that would be found unsuitable for several reasons. Not only would the original excavation of the canal in deep cutting be difficult and costly, but the subsequent maintenance of a clear channel to full depth by dredging or otherwise would be troublesome. It can be readily

understood that the cost and difficulty of excavation becomes very great as soon as spring level is reached. The depth of large canals is, therefore, made as great as may be found convenient under the conditions affecting the question. The width that will give a channel of the required discharging capacity is then found by the help of hydraulic tables.[1]

As examples of the head reaches of canals in cutting, two sections are given (Fig. 52). The upper one is typical of Indian canals; the lower is that of a recently made canal in Egypt. In India, where rain falls heavily, it is necessary to make a

MAIN CANALS IN CUTTING



system of drains on the inside berms to prevent the slopes being worn into gutters. In Egypt the rainfall is so light that this precaution is unnecessary.

Main canals are run with a constant supply, and with a water surface not necessarily above country level. It is, in fact, desirable to keep the water level as low as possible, consistently with a delivery at convenient levels to branch canals, for several reasons. Direct irrigation from a main canal should be discouraged as much as possible on account of the difficulty of effecting a fair distribution of a limited supply of water by

[1] Jackson's "Canal and Culvert Tables," Higham's "Hydraulic Tables," and Colonel Moore's "New Tables," will be found useful. See Appendix II.

any system of rotations when such a practice is allowed. Moreover, as main canals flow with a water surface at a constant level for long periods, it is best to keep the water within soil to avoid the evils of infiltration and consequent waterlogging of the soil outside the canal. To provide for the irrigation of the land adjoining a main canal, parallel high level distributaries should run alongside to take up the direct irrigation.

It is not possible to define in terms that are universally applicable a main canal, a branch canal, and a distributary. It is not always easy to decide where a main canal becomes a branch canal, or where a branch canal becomes a distributary. A branch canal is at any rate intermediate in position and partakes of the nature of the other two. To design branch canals and distributaries correctly it is necessary first to consider what will be the future methods of water distribution. According to the practice common to almost all countries in which irrigation is established, the distribution of water is effected, at any rate during seasons of short supply, by some system of rotation. Under such a system water is alternately supplied and withheld for certain fixed periods, so that each distributing channel flows only for the time required to irrigate the crop depending on it, and not during the intervals between waterings. This method of distribution will be fully described in the next chapter, but it is necessary to refer to it here, as the design of the distributaries has to be based on the method to be adopted. Suppose, for instance, that the rotation programme arranges that water shall be supplied for seven days and be cut off for the following seven. The discharge, which has been calculated on the basis of a continuous flow, must, under such a supposition, be doubled, as it will have to do the same amount of work in half-time. The distributaries of the Ganges Canal in India, as originally designed, did not contemplate any distribution by rotation. Many of them have, in consequence, been lately remodelled so as to enable them to

run every alternate week instead of continuously as they formerly did.

In Egypt, for summer irrigation, the distributaries of each separate system are divided into three groups, to each of which water is given in succession for a third of the whole period of rotation, or interval between waterings. Therefore, as the irrigation has to be effected in a third of the time that would be taken by a constant discharge, the distributary must be capable of carrying three times the discharge calculated on the basis of a continuous flow. It has been shown in Chapter III. that 12 cubic metres per acre commanded is the continuous discharge required to irrigate the summer crops of Egypt, assuming a watering every eighteen days. This being the allowance for a continuous flow, the discharge required to complete the irrigation in a third of the time, or six days, must be calculated at the rate of 36 cubic metres per acre commanded below the point that is being considered.

On the Sone canals in India closures of entire distributaries for half-time were provided for, and the channels were designed to carry twice the volume which would have been allowed with a continuous flow discharge. Mr. Buckley considers this period of closure excessive, and is of opinion that five days' closure in fifteen is sufficient. Agreement between Indian-and Egyptian practice is not to be expected. Irrigation problems in India are more complicated than in Egypt on account of the greater variety and complexity of the conditions. In Egypt, rainfall, being a negligible factor, introduces no complications. The fact also that practically all cultivable land in Egypt is irrigated, so that the area commanded and the total area under cultivation are the same, simplifies many questions of irrigation. That is why Egypt furnishes so many useful illustrations of irrigation principles, the varying factors of other countries being eliminated.

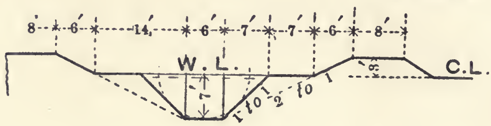
The best form of distributary channel is found by Neville's rule in this way: "Describe any circle on the drawing board;

draw the diameter and produce it on both sides; draw a tangent to the lower circumference parallel to this diameter, and then draw side slopes at the given inclinations, touching the circumference on each side and terminating in the parallel lines. The trapezoid thus formed will be the best form of channel, and the width at the surface will be equal to the sum of the two side slopes." The usual value to give to the side slopes of distributaries is 1 to 1. An ideal section, including the banks, is given in Fig. 53

Distributaries should be so designed, as regards their longitudinal section, that the lands served by them may be readily irrigated free-flow. This principle has been opposed at different

CROSS SECTION OF AN
IDEAL DISTRIBUTARY

FIG 53



times by those who have maintained that lift irrigation is the healthy system, and flush irrigation the reverse. Waterlogging of the soil and salt efflorescence have resulted from the long-continued maintenance of canal water levels above country surface. The remedy for these evil effects of infiltration was held to be a permanent lowering of the canal water levels, and a resort to lift irrigation. But neither India nor Egypt has accepted this view. The advantages of flow irrigation are as obvious as the ill effects of infiltration. The system to be preferred is one that will avoid the ill effects without losing the advantages. The first condition for a healthy system is effective drainage at all times. When that has been secured, no harm will come of high levels in the canals, provided they are produced for short periods alternating with equal or longer periods of low levels. With these provisoes an easy, cheap, and

plentiful water supply is an unmixed blessing to agriculture. A liberal supply of water, combined with a perfect system of drainage, will provide the means for washing salt out of the soil that is impregnated with it, if the water is delivered free-flow. It would be useless to attempt such washings where water has to be lifted, as it would not pay. To prevent any harmful effect from infiltration due to high levels, the canals should be run at high and low levels alternately. The system of irrigation by rotation lends itself to this arrangement. Such an alternating or intermittent supply keeps the water in the soil from stagnating, gives free-flow during the high level period, and affords relief to the drains during the low periods by reducing the excess resulting from wasteful irrigation. The canals also themselves, when low, act as drains to those lands alongside them which have imbibed too freely during the high level period.

There is another reason for designing the distributing canals so that they may deliver their water free-flow. During the floods of certain rivers the water carries along with it rich fertilising matter, brought down from the hills or catchment basins where the rains which cause the floods fall. It is most desirable to secure on the fields as much of this silt as possible. Therefore, during flood, the canals should be run with liberal supplies, and at such levels that the water can be readily made use of. But there must be limits to this liberality, as, otherwise, either the drains will have to be made extravagantly large, or they will be called upon to do more work than they can efficiently perform. The alternation of weeks of high level and of reduced supply—not necessarily low supply—seems to afford the most convenient compromise that gives the advantage of a sufficiently liberal supply without the detracting accompaniment of bad drainage.

The distributaries, therefore, must be designed to give free-flow irrigation when running full supply. Under the rotation system they irrigate only when at full supply. A suitable full

supply level for the water of a distributary will then be represented by a line approximately parallel to the land surface and about a foot above it.

Those branch canals which perform the duty of direct irrigation should be designed as if they were distributaries; while those that act in the same way as main canals, that is, merely as carriers of water to the heads of the distributing channels, should be reckoned main canals.

The application of the foregoing principles may be illustrated by taking the case of the distributing canals of the delta of Egypt. During the period of short supply in summer a three-section rotation is applied; that is, each of the three sections into which separate canal systems are divided has water for a third of a rotation period (or interval between successive waterings), and is without it for two-thirds. If the full period is fixed at eighteen days, each section gets water for six days and is without it for twelve. As has been already shown, the distributing canals must carry during their supply period a discharge calculated at the rate of 36 cubic metres per day per acre commanded. During the flood season the programme is altered. The distributing canals are given full and reduced supply in alternate weeks. The allowance in flood is at the rate of 25 cubic metres per day of continuous flow per acre commanded. If the flood rotation programme provided for the whole volume being delivered in one half-period, and nothing in the other half-period, the channels would have to carry 50 cubic metres per day per acre for half-time. As this figure is greater than the summer discharge of 36 cubic metres, this larger flood discharge would determine the dimensions of the canals. But it has been found undesirable to reduce the discharge to nothing in one half-period, and better for the general convenience to arrange that the discharge of the low period may be about half the discharge of the high period. Thus the high period discharge would be at the rate of 33 cubic metres, and the low period discharge at the rate of 17 cubic metres, per day

per acre. As, however, the summer programme requires that the canals shall be able to carry a discharge at the rate of 36 cubic metres per day per acre, this figure, being the larger, determines the dimensions of the canals, and represents full supply. The distributing canals during the flood would then run full supply one week, and at reduced supply, or at the rate of $(50-36=)$ 14 cubic metres per day per acre, the alternate week.

Summing up the results obtained in the particular illustration chosen, the main canals (and branch canals serving as carriers only) would be designed to carry a continuous discharge calculated at the rate of 25 cubic metres a day per acre commanded; the distributaries (and branch canals acting as distributing channels) would be designed to carry a maximum discharge calculated at the rate of 36 cubic metres a day per acre commanded. The flow of the latter in summer would be intermittent, the water being cut off for periods equal to double the duration of the periods of supply. In the flood season the canals would flow alternately at full and half-supply for equal periods.

This example is no more than an illustration of the application of principles to a particular case. Every country will have its own peculiar conditions which will determine how the principles of design should be adapted to its convenience and advantage.

A scheme of drains should form part of the original project for the irrigation of any tract of country that includes low-lying lands. But it can scarcely be said that this rule has been followed in the past in those countries where irrigation has been practised. The history of irrigation shows rather that canals have first been made and used for a long time before any attention has been paid to drainage. It was assumed that it could take care of itself, and that rainfall and the surplus water of irrigation would disappear somehow by evaporation,

absorption, or otherwise. To some extent, in high-lying lands, drainage will take care of itself provided the natural drainage channels are not interfered with. But in low-lying lands the evils that result from neglect of drainage will inevitably call attention to the subject. The postponement of its consideration until after the canals have been made is now recognised as wrong in principle. This does not mean that a complete system of drains should be laid down at the time of the carrying out of an irrigation project. But the main drains and branches, and all drains in fact which it is certain will be necessary, should be included in the scheme. The necessity for additional drains will doubtless arise as the irrigation develops, but they can be made when the want of them is felt. The history of the construction of the Ganges Canal in India and its subsequent remodelling to provide for drainage, which had been disregarded in the first instance, forms an instructive lesson for irrigation engineers. In Egypt twenty years ago there were no drains, and much land had been ruined for want of them, and more was in process of being ruined. Since then hundreds of miles of drains have been dug, and not only is the further spread of the evil stopped, but the lands that were ruined are being reclaimed to cultivation. In the west of the United States the same mistake was made as had been made before in Egypt: natural drainage lines were converted into irrigation channels, with the inevitable result of waterlogging the soil and rendering it uncultivable. The San Joaquin valley in California has suffered from this injurious practice. Most countries, in short, which have occupied themselves with irrigation, have learnt sooner or later that drainage also must receive its due share of attention.

A drain to be efficient must be designed with a waterway of such levels and dimensions that it will carry away the surplus water of the area served by it, with a water surface always well within soil. The water level in the drain should, if possible, be kept at least 2 feet below land surface. The

maximum discharge which should be provided for will be proportional to the area to be drained, and will depend on the rainfall as well as on the description of irrigation practised. Land under rice crops discharges at least double the amount that land under ordinary crops does. If the rainfall is considerable it is probable that land depressions will be well marked and be traversed by natural drainage lines which may take the place of the main drains of an artificial system. But, if that is not the case, the main drains, as well as subsidiary drains, must have sufficient discharging capacity to carry away both rainfall and excess canal water. It is, of course, impossible to lay down what allowance must be made for rainfall when the conditions are not known. The amount of rainfall, its intensity for short periods, the season, the soil, the configuration of the ground, all affect the question, and must be taken into account when the drainage scheme is being elaborated.

Neglecting the question of rainfall, it is possible to state the principles on which the drains should be designed to enable them to carry off the surplus water resulting from irrigation. A system of drains is the converse of the system of canals with which it is associated. The main drain, which forms the tail of the drainage system, corresponds with the main canal that forms the head of the irrigation system; the subsidiary drains correspond to the distributing irrigation channels. As the main canal carries water to the channels which distribute it, so the main drain carries away the water which the subsidiary drains collect and discharge into it. The discharge of the main drains will be more or less constant for prolonged periods, as the total drainage of a large extent of country is, on the average, the same throughout a season. In correspondence with the irrigation periods of rotation, the flow in branch drains will be intermittent. Some will be discharging at one time and some at another, so that those that are discharging are balanced by those that have ceased to discharge, and the aggregate discharge of all the collecting drains of a system

becomes a fairly constant quantity. Hence the dimensions of the main drain should be calculated on the basis of a continuous flow. The question is, what discharge per acre of land served by the drain must be allowed in order to arrive at the amount of run-off. The maximum discharge to be admitted into the canal system for the purpose of irrigation will have been previously determined as the basis on which the canals were designed. The maximum discharge in any drain should naturally be something less than the maximum admitted into the canals. For a main drain, below the inflow of the lowest branch drain, it would probably be sufficient to provide for a third of the irrigation maximum. This allowance would contemplate a continuous flow. But on the branch drains the discharge becomes more intermittent and fitful the higher in the system the drain may be. For this reason the minor drains must be allowed a comparatively large section, as they will have to carry off the water as it reaches them, that is, in half time or third time. In the case of the main drain a third of the irrigation volume was assumed to run off, but in the case of the minor branch drains at the upper extremity of the drained area it is well to calculate that half the maximum irrigation allowance per acre, used to determine the dimensions of the distributaries, may have to be carried by the drain at some time or other. The drains which are intermediate between the uppermost branches and the main drain would be given sections capable of discharging volumes calculated at a rate per acre which would be less than that used for designing the minor branch drains above them, but greater than that provided for by the dimensions of the main drain.

As the delta of Egypt has furnished an illustration for canal design, it will be useful to complete the example by applying the foregoing principles to its drainage system. For this purpose Egypt is the most favourable instance to select, since, as has already been stated, its rainfall is negligible and the whole area commanded is irrigated. The maximum discharge

admitted into the main canals is at the rate of 25 cubic metres a day per acre commanded. Therefore the main drain, which should carry about a third as much, will be designed to discharge at the rate of 8 cubic metres a day per acre served by it. The distributing canals are designed to carry a maximum of 36 cubic metres a day per acre commanded. The minor branch drains at the upper end of the drainage system, which should carry half as much, will be designed to discharge at the rate of 18 cubic metres a day per acre served by them. The intermediate drains, according to their position on the drainage system to which they belong, should be made capable of carrying 15, 12, and 10 cubic metres a day per acre.

Deep drains are preferable to shallow ones, as weeds grow less readily in the former. Drain water, being clear, encourages the growth of weeds, whereby the efficiency of drains is often much diminished. A low rate of velocity is also favourable to weed growth. It is therefore better to give depth of channel in preference to width to the extent that is practicable, and also to give a comparatively steep gradient to the drain so as to secure a high velocity of flow. This latter is often impossible, especially in main drains near their outfalls if the land which they drain is flat. Depth of channel must then be relied upon to discourage weed growth. In large systems the maintenance of the depth can only, as a rule, be arranged for by dredging. To secure a sufficient depth and velocity of flow for the continuous discharge of the main drain, it is necessary to avoid giving the channel excessive dimensions. If the discharging capacity of the drain is just sufficient, but no more than sufficient, so that it will carry away the drainage water with a depth that will prevent weed growth, the drain will maintain its efficiency for a longer period than it would do if it were of larger section and flowed with less depth.

CHAPTER IX.

MASONRY WORKS ON IRRIGATION CANALS.

MASONRY works are required on the distributing channels of an irrigation system to give effective control over the supply and its distribution. They may be classified as follows:—

(1) Regulating works to distribute the water and control its levels, such as head sluices, regulators, escapes, and culverts;

(2) Works to overcome an abrupt and decided change of level in the canal system, such as falls and rapids or cascades;

(3) Works to provide for crossing drainage lines, such as aqueducts and syphons;

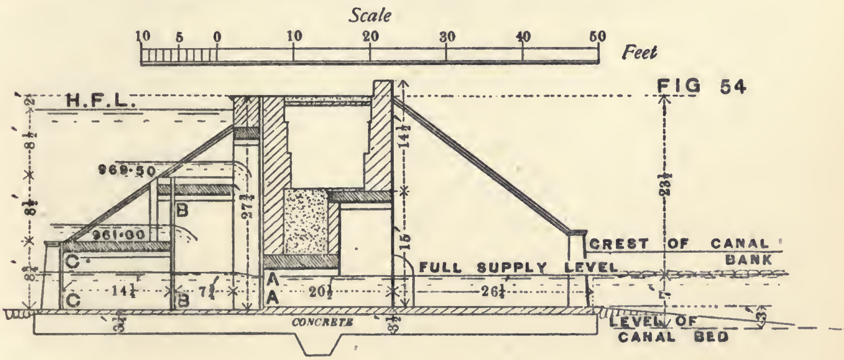
(4) Road bridges at traffic crossings.

The head sluice of a canal controls its supply. In the preceding chapter it was pointed out that, to meet the silt difficulty, the head sluice of a main canal fed from a muddy river should be given a considerable length and a raised sill, and that the shutters should be worked in such a way as to admit only the upper water. Mr. Buckley, who was an advocate of these principles and, as chief engineer of Bengal, a practical demonstrator of their soundness, gives the following description of the Trebeni Canal head sluice (Fig. 54):—

"The Trebeni Canal head sluice, which is now" (1905) "under construction in Bengal, stands on the bank of the Gunduk river, at a point where the flood rises over 20 feet. The sluice is designed to give the required discharge with a depth of 2 feet of water flowing over the tops of *kurries* or horizontal baulks. The vents A A have draw-gates, worked by a screw and capstan on the parapet. These vents will be used to some extent for

regulation, and will be closed entirely if the high floods carry down heavy silt, which would be likely to choke the canal. When the flood level is more than 2 feet above 969·50 the supply will be drawn in over the top of the arch platform which lies at that level. At that time the vents B B and C C will be entirely closed. As the flood falls below the platform the *kurries* in the vents B B will be removed, as required, and the water will be drawn in over the top of them into the canal. When the water level in the river falls to less than 2 feet above the top of the platform at 961·00 the *kurries* in the vents C C

TREBENI CANAL HEAD SLUICE



will be removed, as required, and the discharge will be regulated over the tops of the *kurries* in those vents."

This is an excellent example of the application of the principles on which a head sluice should be designed with the object of excluding heavy silt from a canal. In this case there is no raised sill, but the whole floor is 3 feet above the canal bed level. There are twenty-two vents in this sluice, each 6 feet wide at A, 7 feet at B, and 7 feet 6 inches at C.

Vents of head sluices vary in width from 3 feet to 16 feet. In Egypt the head sluices of the largest canals have vents of 5 metres (16 feet 5 inches) width. The waterway allowed is determined by the discharge required and the available head at

different seasons. It is a good rule to allow a liberal waterway with a margin for meeting the demand for an increased discharge which future developments may create. The extra allowance, beyond the area calculated to be necessary, might conveniently amount to 10 per cent. in large works and 25 to 30 per cent. in smaller works. The floor of a head sluice and its up-stream and down-stream aprons will have to resist the same forces and be subjected to the same action as a river barrage, described in Chapter VI., and therefore should be similar in design. Two large head sluices, lately built at Assiout and Zifta, in Egypt, have been given practically the same cross-section as the river barrages with which they are associated. Head sluices, however, with narrower vents, and at the head of branch canals, can be built of lighter construction than head sluices on a river, as the up-stream water level is not subject to such great variation in a feeder canal as it is in a river. The design of the superstructure depends to a great extent on the description of regulating apparatus adopted, and sometimes on the necessities of the traffic that will pass over the sluice. The different forms of regulating apparatus will be referred to later in this chapter.

In a general way the principles of design are the same for all canal works of regulation which are subjected to a head of water up stream and to scouring action down stream. The head or the scour may be greater or less, necessitating a modification of the design in those dimensions which are affected by the one or the other. An escape or fall, as a rule, requires ample protection down stream in the form of an extension of the floor, well-revetted slopes, and a talus of heavy pitching, inasmuch as a heavy discharge through it may continue to work under an undiminished head for some time; whereas in the case of a simple regulator, the canal below quickly fills up, and the head is reduced. A basin regulator in a cross embankment works under the conditions of an escape or fall, as it discharges into an open basin requiring an enormous volume of water to

affect its surface level. It is therefore necessary to give the same attention to the down-stream protection of basin regulators as is required in the case of escapes.

Regulators are generally placed where a canal bifurcates, and below the point where a branch canal takes off. They may also be required across a canal immediately below an escape or level crossing. They are, in fact, necessary or desirable wherever a division of the water supply has to be made.

Escapes are the safety valves of a canal system. They supply the means of disposing of any surplus discharge that has to be got rid of, when, for instance, in consequence of a slackening of the demand for water, the irrigating sluices are suddenly shut down. This often occurs after a heavy fall of rain without sufficient warning for the situation to be met by decreasing the discharge entering the canal at its head. Escapes are also useful in case of an accident to any of the canal works requiring an immediate reduction of the discharge. They also assist in producing a high enough velocity in the canal, when it is carrying muddy flood water, to lessen silt deposit, and, later on, when the water is clear and a surplus available, they make it possible to maintain a high current in the canal whereby silt deposits that have formed during flood are diminished by scour. For these purposes escapes are most desirable on main canals and long distributaries, not only at the tails, but at intervals along their courses.

If possible, an escape should discharge into a river or well-defined waterway, and not into a drainage line. This principle, however, cannot always be carried out, and something short of the ideal has to be accepted: a river may not be within reach, and no well-defined waterways, other than drainage lines, may offer themselves.

The design of an escape may be similar to that of a head sluice, a regulator, or a fall, or a combination of them. But, as already stated, the down-stream protection must be adequate. An escape may take the form of a waste weir with a drop, and

be protected down stream by a "rapid" or "cascade," the fall of the water being divided between the drop of the weir and the rapid forming its apron. On the crest of the drop-wall, shutters or baulks or other regulating devices would, if necessary, control the volume escaped.

Basin escapes which have to pass large quantities of water are sometimes formidable works. There is a fine work in Egypt, of modern construction, known as the Kosheshah escape. It was designed to discharge back into the Nile the contents of a chain of inundation basins of an aggregate area of 555,000

KOSHESHAH ESCAPE

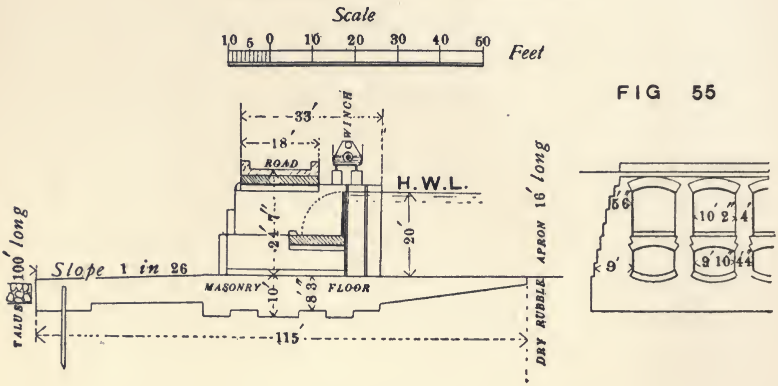


FIG 55

acres. It is capable of discharging 80,000 cubic feet a second under a maximum head of nearly 15 feet. It has sixty upper vents and sixty lower ones of the dimensions shown in Fig. 55. The lower vents are regulated by iron sluice-gates moved in vertical grooves by an overhead winch. They are used to admit water into the basins during the rise of the flood and afterwards to assist in emptying them. The upper vents are used only for the emptying. The latter are fitted with falling gates hinged at their lower edges. A water cushion is provided for the gates to fall upon by giving the upper floor a raised sill of ashlar along its down-stream margin. The upper falling gates can all be let go within a quarter of an hour if desired.

KOSHESHAH ESCAPE.

The object of providing for quick opening is to produce a wave in the river after a poor flood so as to submerge certain high islands and river-side lands which depend on the flood rise for their irrigation but are of too high a level to be reached by poor floods. The artificial wave created by the sudden emptying of the basin contents back into the Nile has often succeeded in effecting the irrigation which the natural flood had failed to complete. Plate VIII. gives a view of part of the Kosheshah escape taken during construction but after the masonry had been completed. The bottom gates were already in their grooves, closing the lower vents, and an upper gate was being put in place when the photograph was taken. In the bay to the left of the one where the gate is being hung both the upper and lower gates are in position, closing the vents; in the bay to the right the upper gate is wanting.

Canal falls or weirs are required at intervals along a canal which has a gradient that is less than the slope of the country through which it runs. If the canal is navigable, wherever such falls are necessary a lock has to be provided for passing boats between the upper and lower reaches.

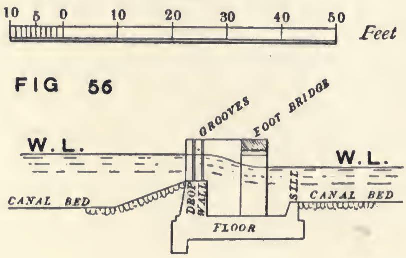
The once favoured form of "ogee" fall has been generally condemned, as falls of this description have given endless trouble, the principle of design being a mistaken one. "Falls" are now usually given a vertical drop wall with a steep face batter. There are various ways of providing resistance to the shock of the falling water. The simplest way, and sometimes the most economical, is to protect the weir floor, where the water falls, with a layer of hard ashlar sufficiently strong to bear the shock, the floor surface being at the canal bed level of the lower reach. Sometimes a cushion of water is formed by building a raised sill along the down-stream edge of the floor. When this arrangement is adopted, the general floor surface may be at canal bed level and the sill be above it. But it is more usual to sink the floor and to make the crest of the sill coincide with the canal bed, as in Fig. 56. Sometimes the cushion of water

is formed by sinking the floor immediately below the fall and sloping it up to the level of the canal bed at the down-stream edge of the floor, as in Fig. 57. In the case of weirs on navigable canals the crest of the drop wall is often raised above the canal bed level of the upper reach, and the water level is sometimes also regulated by planks sliding in iron or masonry grooves above the weir crest, as in Fig. 56.

On the Bari Doab Canal in India many of the drops of the

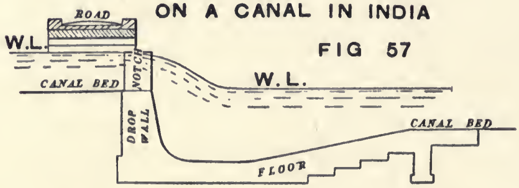
CANAL FALL

WITH WATER CUSHION



NOTCH FALL

ON A CANAL IN INDIA



canal bed are effected by rapids, sometimes in the form of cascades. They are constructed of dry boulder pitching confined in rectangular spaces by longitudinal and cross walls of masonry. The change of bed level is sometimes effected by a rapid with a continuous flat surface slope, sometimes by a cascade with a succession of short drops.

Below all falls there is always the effect of eddies and high velocity currents to be overcome. Various forms of downstream wings, of pitched apron, and of revetted side slopes are

adopted by different designers. There are convex and concave wings, wings splayed at all angles, and wings parallel to the direction of flow. For the pitched length beyond the masonry work there was, not long ago, considered to be virtue in the soda-water bottle form of a more or less pronounced curvature. In Egypt there are a great many escapes and regulators working under considerable heads, which, having been allowed their own way, have scoured out deep and wide pools down stream of the floor, to the danger of the whole work. The best remedy for this has been found to be to make dry rubble spurs parallel to the direction of flow, taking off from the wings. The crest of the spur is usually at or near high water level at its meeting with the wing, whence it slopes gently downwards. Its length depends upon circumstances. The result of making these spurs in many cases has been, not only to stop erosion on the flanks, but to cause the deep pool to silt up to some extent. The principle of these guiding spurs has been consequently adopted in the design of new escapes. The masonry apron and pitching, instead of being horizontal in its longitudinal section, is often given a slope downwards from the pier ends of about 1 in 10, and the pitched talus is continued at the same slope. On the apron in front of either wing a masonry footing is built to prevent the stone spur from sliding on the floor, and the dry rubble spurs are constructed as above described. In India the place of the dry rubble spurs is taken by dwarf walls of masonry. Straight wings with rounded angles at the return walls, or wings with a slight splay of, say, 30 degrees inclination to the direction of flow, are preferred by some to other forms.

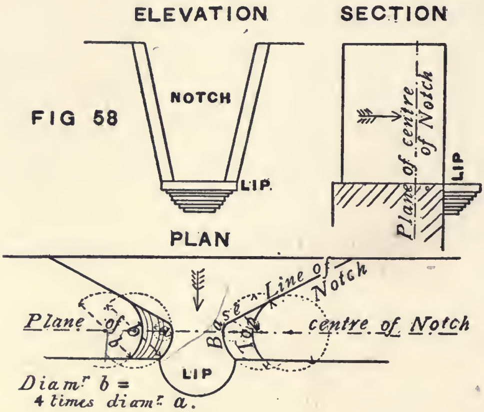
A distinction must be made between escapes which discharge into open basins, or wide spaces, and "falls" in canals of a regular section. In the latter case, as prevention is better than cure, the works should be designed to prevent pooling. It is best to hold the water in check and to forcibly keep it to its ordained channel until it ceases to be turbulent. To allow

it to spread horizontally encourages the formation of eddies. Whether there is anything gained, beyond a water cushion to break the falling water, by sloping the floor and talus downwards is doubtful, as vertical eddies are no more to be desired than horizontal ones.

However, the form of floor shown in Fig. 57 is stated by Mr. Buckley to be peculiarly suitable for checking the ebullitions of the water and reducing it to steady forward velocity. But this form of floor is used in conjunction with a "notch"

FORM OF NOTCH
FOR CANAL FALLS

FIG 58



fall, which works so smoothly that there are no ebullitions to be checked. With this description of fall the difficulties of excessive velocity and great action down stream have been overcome. A sketch of one of these notches is given in Fig. 58 (from Buckley). On the Chenab Canal, in India, falls have been constructed of a row of these notches cut in a breast wall. The principle of the design is that the notches discharge at any given level the same amount of water approximately as the canal above carries at that level, so that there is no increase in velocity in the canal as the water approaches the fall (except

for a few feet close to the notch), but a uniform flow and a uniform depth is maintained. No heading up by planks at these falls is either arranged for in the design or permitted. They are, in fact, not suitable for situations where heading up is necessary, either for the sake of navigation or for any other purpose. The bases of the notches of the Chenab Canal falls are at the canal bed level of the upper reach, and the crest of the breast wall is above full supply level. At the foot of each notch there is a lip projecting beyond the lower surface of the breast wall, which has a great influence in spreading the stream and determining the form of the falling water.

In the Fayum Province, in Egypt, the distribution of the canal water is to a great extent effected by a description of weir, or rather collection of weirs, known as a *nasbah*, an Arabic word signifying "proportion." It is an automatic distributor of the discharge of a canal among its branches. It is placed where a channel divides up into two or more branches, and is made up of weirs across the heads of the branches united into one combined work. The level of the weir sills is the same throughout, but the width of the waterway, or length of weir crest, in each case is made proportional to the area of land served by the branch. Provided that the weirs have all a free fall —that is, that the level of water in the reach below the weir is lower than the sill of the drop wall—the distribution of water is practically fair. The longer weirs pass rather more than their theoretically correct discharge; but, as a rule, the water passing them has farther to go to reach its destination than that which passes over the shorter weirs, and will suffer some loss from evaporation and absorption on the way. The arrangement works well and gives satisfaction to the cultivators, who are the most interested in the just distribution of the water. The system can only be employed where the land surface has a slope sufficient to admit of the introduction of free fall weirs at the points of distribution in a canal. The

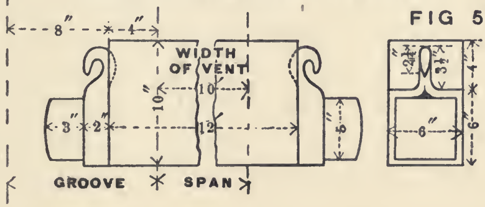
Fayum is the only province in Egypt where such a system is possible.

A most important part of all regulating works is the apparatus that controls the levels and discharges of the canals. In out-of-the-way situations, where skilled labour and mechanical appliances are scarce, simplicity of design is a great desideratum. The earliest form of regulating apparatus was probably the needle or vertical closure, prevalent throughout Egypt some twenty years ago, and still common on the Sind inundation canals in India. In this system horizontal wooden baulks or rolled iron joists, fixed in the masonry faces of the vents, bear the pressure of the vertical needles. The needles are simply baulks of timber placed vertically side by side across the regulator vents to effect a total or partial closure as may be desired. They are put in place or removed by some mechanical contrivance overhead. In Egypt, a few years ago, this generally took the form of a lever of primitive construction, any loose timber that was handy being employed; the parapet wall of the regulator was made to serve as the fulcrum. The needles were clumsy, difficult to handle, and unsuitable where tight closures were required. The system was from time to time improved upon in its details. A movable frame was devised to carry the horizontals so that they could be put in place when required. The needles also were made lighter, and were constructed with V-shaped edges, like sheet planking. But, in spite of these and other improvements, the system of closure by vertical needles has died out in Egypt, and has been replaced by the system of closure by horizontal baulks or planks working in vertical grooves. The horizontals are easy to handle, require few men to work them, and give a tight closure. The pattern of plank which is now generally used is that shown in Fig. 59. A groove of 8 to 10 inches depth is required with this description of plank to give a sufficient bearing on the full-section length between the end hooks.

The planks are raised by iron rods provided with eyes at their lower ends for engaging the hooks. The hooks lie within the grooves, so that the rods, as they are passed down, are sheltered from the current flowing over the planks, and it is therefore an easy matter to feel for and find the hook. The greatest objection to the system of horizontals is the difficulty of getting the planks down in deep water against a head. The method usually employed is to drop planks into the grooves till the top one is above water, and then to jump them down with an iron "monkey." The grooves in which the planks work are either cut in ashlar stone or are of cast iron. It is not

HORIZONTAL PLANK
USED FOR CLOSURE IN EGYPT

FIG 59



usual to employ this system of horizontal sleepers, or planks, for spans exceeding 10 feet.

For larger spans wrought iron gates are substituted for the wooden planks. But the system is only a modification of the system of closure by horizontal wooden baulks. The gates slide in cast iron grooves in the same way as the horizontal planks, and are raised and lowered by means of travelling winches overhead. A suitable height for a gate is 8 to 10 feet. So that, where the height of closure is 14 to 20 feet, a pair of gates in each opening, working in double grooves, is provided. There are instances of regulators with three gates and triple grooves in each vent. Gates of this description are provided with rollers whose axles are fixed to the gates; otherwise the weight of the gates would not be able to overcome the friction when it was desired to lower them against a head. When the

gate reaches its lowest point it ceases to bear on the wheels, and slides on to an inclined plane in the groove, so that a tight closure is secured.

For spans over 18 feet "Stoney's" shutters, which are counterbalanced and move on roller beds, are much in favour. But their province is rather rivers than canals, as canal regulators rarely reach the dimensions of works for which Stoney's gates are best adapted.

For the smaller canal regulators, with sluice openings of 2 to 6 feet width, a gate of wood or iron controls the discharge. Screw gearing, with a capstan in some form above, is ordinarily used for lifting and lowering these gates. Sometimes two, and even three, shutters in one vent are operated in the same way by screw and capstan, the shutters sliding in double or triple grooves, as in the case of gates worked by overhead winches.

On the Idaho Canal, in the United States, the Cameré curtain of the Seine weirs is used for regulating sluices. It is fitted to the head of the Idaho Mining Company's canal, which has eight openings, 8 feet wide by 19 feet high. The roller curtains, which close the openings, are made of steel plates and angle iron to a height of 10 feet from the floor, and of pine slats, 6 inches wide, above that height. The bottom of the curtain is fastened to a cast iron roller, on which it is wound up by means of a chain worked by an overhead winch. This form of closure is suitable for a sluice with high vents where it is desirable to keep the superstructure low, and space for housing gates above water level cannot be conveniently provided.

In the preceding chapter, when considering the alignment of canals, it was laid down as a general rule that canals should be so aligned as to avoid crossing natural drainage lines as much as possible. But it is not always possible to avoid doing so, especially along the first section of the canal, which lies between

the source of supply and the point where irrigation begins. It is therefore necessary to provide for the passage or disposal of the discharge of drainage lines or natural watercourses encountered by the canal. In some cases their waters can be diverted into new courses and a crossing be avoided. But when this is not the most advantageous method, one of the following arrangements must be adopted.

Local drainage of limited areas may be discharged through inlets into the canal if the volume of water to be got rid of is quite small. Such works are always of little importance, as it is not permissible to deal with large volumes of water in this way.

Where the quantity of drainage water to be dealt with is large, it must be provided with some means of passing the canal and of flowing forward in its natural channel beyond the point of crossing. A drainage line in this connection signifies any natural watercourse, such as a river, torrent, or stream, which carries the rainfall that drains off its catchment. There are three ways of arranging for the crossing: the drainage discharge may either pass into the canal and out again on the opposite side by a level crossing; or it may pass over the canal by what is called in India a superpassage; or it may pass under an aqueduct carrying the canal. The respective levels of canal and drainage may be such that either of the two latter arrangements may take the form of a syphon, and the terms "superpassage" and "aqueduct" would no longer be applicable. A superpassage is an aqueduct, but irrigation terminology in India distinguishes between an aqueduct that carries a canal over a drainage line and one that carries drainage water over a canal, the latter being technically called a superpassage. The choice between the different descriptions of work for any particular crossing depends chiefly on the relative levels of the canal and the drainage channel and on the respective cost. If the canal is navigable, it must, of course, be uppermost. If levels alone decide the matter, it would be natural to adopt a

level crossing when canal and drainage channel are at nearly the same level, an aqueduct when the canal is higher than the drainage, and a superpassage when it is lower. If a level crossing is for any reason inconvenient, the drainage can be passed in syphon under the canal, which is generally a preferable arrangement to passing the canal under the drainage, but not always so. There are some situations in which sudden floods may bring down detritus from the hills of the catchment and carry it into the syphon, thereby blocking the waterway. The result may be the destruction of the syphon and the breaching of the canal. Under such conditions it would seem to be the safer arrangement to pass the drainage in the open channel above and the canal in syphon below; but torrents which carry detritus along in any quantity will give trouble in either case.

The most magnificent specimens of aqueducts at drainage crossings are to be found in India. The Solani and Nadrai aqueducts are the largest in the world. Mr. Buckley gives the following figures, which will convey some idea of the dimensions of these two splendid works:—

	Solani Aqueduct.	Nadrai Aqueduct.
River waterway	13,000 square feet	21,600 square feet.
Canal waterway	1,600 ,,	1,040 ,,
Canal discharge	6,780 cusecs	4,100 cusecs.
Arches and spans	15 of 50 feet	15 of 60 feet.
Width between faces	195 feet	148·7 feet.
Length	1,170 feet.	1,310 feet.
Depth of foundation below river bed	19 feet	52 feet.
Total height	56 feet	88 feet.
Cost	32,87,000 rupees (£219,000).	44,57,000 rupees (£297,000).
Time taken in building	7 years	4 years.

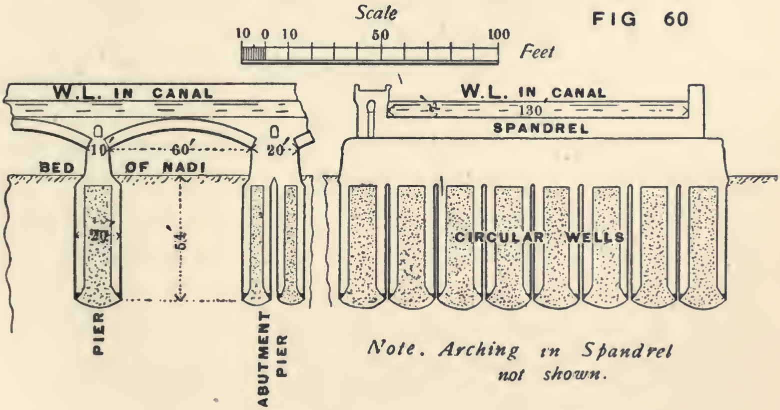
The existing Nadrai aqueduct replaces its predecessor, of insufficient waterway, which was wrecked by an abnormal flood. A cross-section and part longitudinal section of the new work is given in Fig. 60. It was originally intended to

add a sunken floor 10 feet below the river bed, but during construction it was decided to omit this, except in the two end spans, as the clay substratum found below the sand was considered to have sufficient resistance to scour without masonry protection. A protective floor is, however, often added in works of this description. The Nadrai aqueduct will serve as an illustration of this type of work, whether aqueduct or superpassage. The maximum drainage discharge in the upper

NADRAI AQUEDUCT

OVER THE KALI NADI

FIG 60



channel of a superpassage is, however, generally larger than that of the canal below, requiring a modification in the design as regards the relative dimensions of the upper and lower waterways. The discharge which passes over the Budki superpassage in India reaches the high figure of 34,000 cubic feet a second. In the design and construction of such works particular attention must be paid to the wing walls and to the bond between the earthwork of the upper channel and the masonry duct. The wing walls should be given ample length, and all possible precautions should be taken to prevent any creep of water along their faces from the upper to the lower

channel, as any such defect would develop, under the constant head of water, into a disastrous breach.

There is another respect in which liberality of design is advisable in works which have to pass drainage discharges. The waterway provided should be at least sufficient to pass the maximum flood safely. But it is not always easy to determine even approximately what the maximum flood may amount to. The case of the first Nadrai aqueduct, which was carried away by a flood of six times the volume which the design had contemplated, has already been used in Chapter V. as an illustration of the difficulty of calculating discharges from catchments. There is another instance of a serious under-estimate of the maximum discharge of a drainage channel on which a design was based. A hill torrent, with a catchment area of 172 square miles, passes underneath the Thapangaing aqueduct in Burma. The original estimate of the maximum flood was 5,347 cubic feet a second; a later calculation increased the figure to 17,760 cubic feet a second. The Inspector-General of Irrigation ruled that the work should be designed to pass a flood of 24,000 cubic feet a second. The work was designed accordingly and put in hand. While it was under construction the Thapangaing river rose 20 feet in five hours, discharging 56,273 cubic feet a second. Since the design provided waterway for less than half this discharge, the work had to be modified and allowance made for a discharge of 60,000 cubic feet a second. As the aqueduct was partly built, it was desirable to adhere to the original design as far as possible. The design was, therefore, altered so as to provide for passing the drainage discharge partly under the aqueduct carrying the canal and partly across it, so that the work has become a combination of an aqueduct and a level crossing.

A level crossing is controlled by three regulating works, namely, an inlet to admit the drainage discharge into the canal, an escape opposite the inlet to pass it out again, and a regulator on the canal down stream of the level crossing to

provide against fluctuations of the canal supply, which might otherwise be occasioned by the passage of the drainage water across the canal. The discharge passed across in this way is sometimes considerable. The Rutmoo torrent, for example, which is carried across the Ganges Canal by a level crossing, has a discharge of about 30,000 cubic feet a second.

In the United States wood has been much used in the construction of aqueducts. The wooden channels are called "flumes," a term commonly employed for wooden structures which carry the water of a canal either round steep rocky hillsides or across drainage lines. But these wooden irrigation works belong to a pioneer stage. Not many years hence they will be obsolete, and, like wooden battle-ships that have done good service in their day, they will be regarded as interesting survivals of an old order that is past. Wood will be replaced by the more durable materials masonry and iron. There are some remarkable instances, in the west of the States, of flumes constructed on a steep hillside to save the cost of excavation. They are known as "bench" flumes. The bench flume on the High Line Canal in Colorado is over half a mile in length, with a cross-section 25 feet wide and 7 feet deep. Its discharge is 1,184 cubic feet a second. The San Diego flume in California is 36 miles long, which is the entire length of the canal, so built to avoid loss by absorption.[1] Some remarkable syphons have also been made of wood.

For aqueducts of small dimensions iron is a convenient material to use. To prevent leakage between the ends of the iron channel and the masonry of the abutments, a junction must be made which will have play enough to allow of the expansion and contraction of the iron. One way of doing this is to give the ends of the aqueduct a bearing on a cushion of felt soaked in tallow, which is let into the stone of the abutment. This is a security against a leak along the bed. The sides also require staunching. To provide for this, lead

[1] "Manual of Irrigation Engineering," by Wilson, p. 258.

sheeting is attached to the iron of the aqueduct along the bed and up the sides, and grooves in the masonry made to receive the projecting outer ends of the lead. The grooves are then filled up round the lead with a mixture of tar, pitch and sand poured in hot.

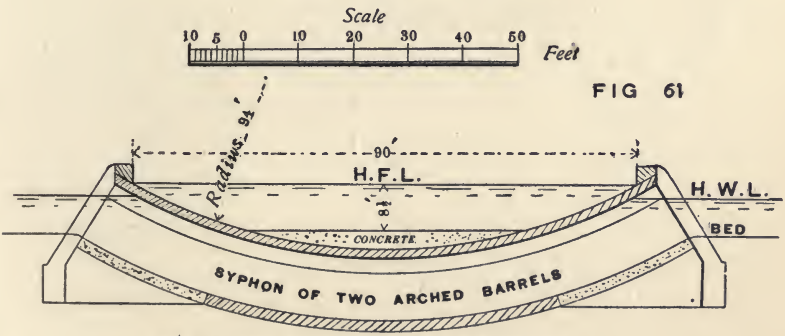
If, when canal and natural stream are about the same level, it is not convenient for any reason to resort to a level crossing as the means of passage, a syphon must be substituted either to carry the canal under the stream or the stream under the canal. In the latter case the work is sometimes called a syphon aqueduct; in the former it might consistently be called a syphon superpassage. In the irrigation literature of the United States a syphon is usually, with more technical accuracy, designated an "inverted siphon."

The design of a masonry syphon is affected by the following considerations. As it has to pass below the channel of an upper watercourse, its foundations generally descend to a considerable depth below the land surface. The deeper they go, the more trouble may be expected from springs over the foundation bed during construction. The designer bears this in mind, and gives the barrels of his syphon width in preference to height. But a syphon is subject to upward pressure against the roofing of the barrels, due to the head of water under which the syphon may be working. To resist this and prevent the pressure from lifting the crown of the syphon, there is the combined weight of the masonry and of whatever water there may be in the channel over the syphon. As it is possible that the upper channel may be dry when the syphon is working under its maximum head, this unfavourable condition must be assumed as the basis of design, and such a thickness of masonry be given over the syphon that its weight may be sufficient to overcome the upward pressure of the water. There are many instances of syphons blowing up in consequence of the water pressure exceeding the weight of the overhead masonry. There are, however, syphons in existence which hold together, although the weight

of masonry over the barrels is insufficient by itself to resist the water pressure. These owe their continued existence to the fact that the tensile strength of masonry joins forces with the weight of material in opposing the lifting force. But, in designing, it is advisable to provide sufficient weight above the syphon vents to give security without taking the strength of the mortar joints into account. The thickness of masonry that it is on this account necessary to provide over the syphon affects the depth to which the foundations must be carried. The ordinary rule

SUPERPASSAGE

ON THE NIRA CANAL INDIA



SECTION ALONG AXIS OF BARREL

of thumb is to make the thickness of the crown of a syphon equal to four-tenths of the maximum head.

Various devices have been resorted to with the view of reducing the depth of the foundation bed. On the Nira Canal in India a peculiar type of syphon has been adopted which makes use of the principle of the arch to resist the upward pressure. The syphon in longitudinal section is given the form of an arch, so that the weight of the outer ends is utilised to resist the upward pressure in the tubes, and the syphon roof may be consequently lightened. Fig. 61 gives a sketch of this arrangement.

Another device is the ingenious one adopted for the Ravi

syphon in India. The diagram Fig. 62 will best explain the principle of construction. Iron straps under the inverts below the vents are connected by iron vertical ties with horizontal girders above. Between the girders an upper row of inverts transmits the upward pressure to the girders, which cannot move without lifting with them the lower inverts and superincumbent masonry. The weight of the inferior masonry is thus utilised to resist the water pressure, and, therefore, the thickness above the vents can be reduced.

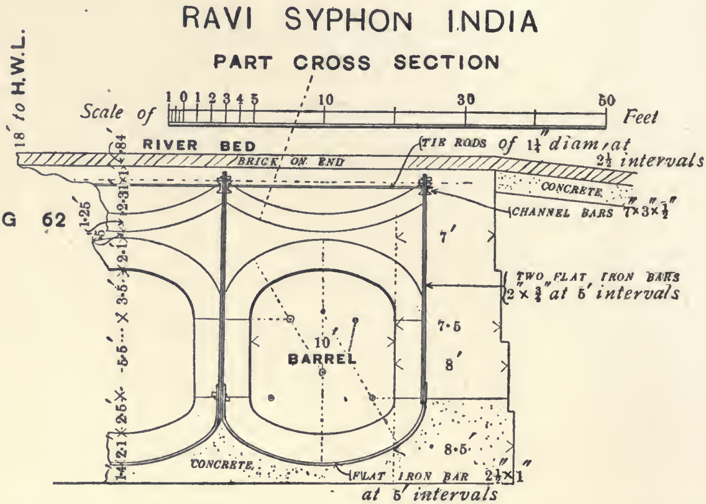


FIG 62

There are two forms of syphon which are common. In the one the tube is horizontal throughout, and the entry and exit of the water take place over the sills of a vertical breast wall, as in the sketch Fig. 63. In the other form, the ends of the tube are sloped to effect the change of level between the syphon waterway and the channel on either side of it, as in the sketch Fig. 64.

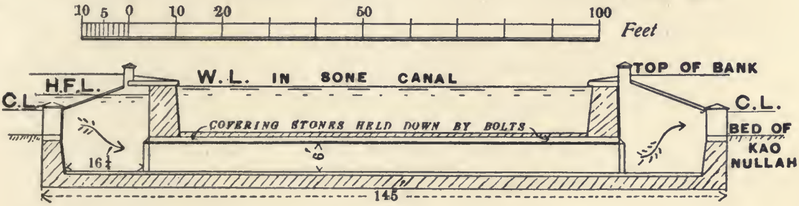
The area of waterway to be allowed in a syphon depends upon the head under which it will work and the consequent velocity of flow. If a head sufficient to produce a velocity of from 5 to 8 feet a second is permissible, the syphon should be

given a waterway which will pass the maximum discharge at that rate of flow. It is advantageous to obtain a high velocity of flow in a syphon, inasmuch as it keeps the barrel free of deposit.

To avoid the difficulty of deep foundations, syphons are often made of steel tubes, bedded, as a rule, on concrete, and some-

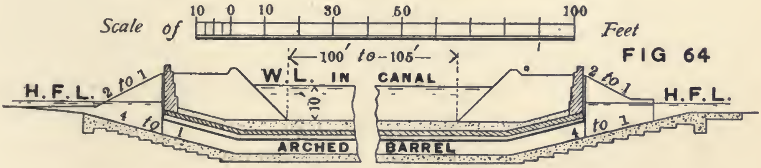
KAO NULLAH SYPHON INDIA

FIG 63



SYPHON ON CHENAB CANAL

FIG 64



times encased in it. If, however, the concrete casing is not strong enough alone to act as the syphon barrel when the metal perishes, there is not much gained by adding it to the tube. If, on the other hand, it is strong enough, the internal tube might as well be omitted in the first instance. Even the concrete bed is sometimes omitted. A pipe syphon without any concrete can be laid in a flowing canal in the manner described at the end of Chapter VII.

CHAPTER X.

METHODS OF DISTRIBUTION OF WATER, ASSESSMENT OF RATES, AND ADMINISTRATION.

WHEN the means of distributing water have been provided in the form of canals with a complete system of regulating works, the problem of distribution is not thereby wholly solved. The method of distributing water from a canal system is almost as important a matter as the design of the works of distribution. The full "duty" can only be got out of a given quantity of water by the application of methods best adapted to the conditions that prevail in any particular case. The subject of water "duty" has already been dealt with in Chapter III., and the influence of methods of distribution on the designing of canals has been referred to in Chapter VIII.

If the supply of water in the main source is greater than the demand, as measured by the needs of the crops to be irrigated, the main canals will be given the necessary discharge to meet the demand. What the discharge should be is determined by the actual area of crop and the accepted "duty" of water for that crop on the particular canal under consideration. If, on the other hand, the supply of water is less than the demand, one of two things must be done; either the area of crop must be limited to that which the available supply is capable of irrigating with the accepted "duty" of water as the basis of the calculation of the area irrigable, or else the demand must be met by making the water irrigate a larger area than the accepted "duty" provides for. But in the latter case, since the area of crop matured will be larger, each acre of it will receive less water, or, in other words, waterings at longer

intervals apart, than the accepted "duty" assumes to be most conducive to the well-being of the crop. An example will be given later on of the adoption of the latter alternative in actual practice. If there are several main canals drawing from a source of supply which is inadequate to meet the demand, and if all the lands have equal claims to the water, the partition of the supply would in fairness be made in proportion to the respective areas commanded by the canal systems on which the lands depend for their irrigation. Each system would thus get its fair share of the available supply, and the question as to whether the crop area should be limited, or a reduced quantity of water per acre be allowed, could be settled for each system independently of the others as might seem best.

When there is a sufficiency of water to satisfy everybody, each individual cultivator might be allowed to help himself if the water were to be given without price. But, even if there be a sufficiency, the water supplied has to be paid for in some form or another. The water rate may be levied on the area of crop either brought to maturity by irrigation, or given a single watering, or irrigated for certain months. The cultivators pay an amount proportional to the area of crop irrigated and dependent on the nature of the crop, some crops requiring more water than others to bring them to maturity. The watered field and the standing crop furnish the data required for calculating the amount due from the cultivator. The objection to such a mode of assessment is that the cultivator has no inducement held out to him to economise water.

The other method of assessment is to charge the water rate on the actual quantity of water used. This method requires some means of measuring the water. Different forms of water meters, or modules, have been invented for the purpose; but the conditions of flow in open irrigation channels do not lend themselves to the accuracy of measurement which is attainable with water meters in pipes flowing under considerable pressure, as in the case of a city supply system. Some of the modules

devised are ingenious, but they are only suitable for small discharges and for use in countries, such as Italy, where the ethics of irrigation have reached such an advanced stage of evolution that "it is thought apparently as discreditable to appropriate an unfair supply of water as to steal a neighbour's horse, as discreditable to tamper with the lock of the water module as with the lock of a neighbour's barn."[1]

When the supply of water is not in excess of the demand, an economical and just distribution depends more on correct methods of administration than on the perfection and completeness of the regulating works. All countries that have practised irrigation on a large scale have found it necessary to adopt some system of "rotation" whereby water is alternately supplied and withheld for fixed periods. Under this system the total area requiring irrigation is divided up into two or more sections, and each section in succession is given water, while at the same time it is withheld from the other sections. The duration of the period of supply is proportional to the area of crop included in the section whose turn it is to be watered. The more perfect are the methods of administration and the means of regulation, the more minute can be the subdivision into sections, and the more exact will be the just distribution of water. But there are practical considerations which impose a limit on the subdivision. The operation of irrigating a single acre takes a certain time, say two hours, and requires a certain discharge, say 2½ cubic feet a second, to complete the watering. Theoretically double the discharge should complete the irrigation of the acre in one hour, but practically the cultivator would find that he could not lead the water about his field at the pace required to complete its irrigation in this short time. As a rule, the subdivision does not go so far as to create sections of so small an area as a few acres; but in Italy, for instance, where distribution of water is carried out in a more

[1] Colonel Sir C. Scott-Moncrieff's address, British Association, 1905.

perfect manner than in any other country, the sections are so small that the duration of the supply periods is reckoned by hours, and not by days. Each cultivator is allowed the use of the water for a number of hours proportional to the area of his crop, and pays, according to the area he waters, his contribution towards the total cost of the maintenance of the irrigation system, and his share of the sum which has to be paid to the Government.

In France also the rotation periods are measured in hours. Whatever the area may be, water is supplied to cultivators at a constant discharge of 30 litres (1·06 cubic feet) per second. The period of flow allowed is reckoned at the rate of five hours per hectare (two hours per acre). As the land is much subdivided and the irrigation has to be continued by night as well as by day, the rotation programme is so drawn up that the same people may not always get their turn during the night. This is arranged for by making the interval between waterings so many whole days and a fraction of a day, the odd hours being introduced for a similar purpose to the dog-watch on a ship. The intervals between waterings, in the case of land devoted to market gardening, are from six to seven days. The irrigation season lasts about six months, so that about thirty waterings are given to the irrigated lands. With intervals between waterings of six and a half days, and allowing five hours per hectare, a discharge of 30 litres (1·06 cubic feet) per second would irrigate an area of 30 hectares (74 acres) of crop. The allowance made provides a volume equivalent to a depth of $2\frac{1}{8}$ inches over the whole area irrigated for each separate watering.

In Spain also the distribution periods are sometimes measured in hours. The irrigated lands of the Henares valley, for example, are divided into plots of about 800 acres. Each plot is served by a branch canal taking off from the main canal. The branch canal is fed through a module, a continuous discharge at the rate of 1 cubic foot a second for every 156 acres being allowed. The fields are irrigated by a number of distributaries taking off from the branch canal. The whole discharge of the branch

canal is turned into each distributary in succession, and each individual landlord or tenant is given the water for a period, measured in hours and minutes, proportional to the area of the crop on his holding. In this way each separate holding gets a watering at regular intervals.

In India the rotation system, copied from Europe, is known among the natives as irrigation by *tatils*; Egypt copied it from India, and the fellah calls it irrigation by *manawabah*; in Java, where also it is practised, it is called the *golongan* system, all these expressions signifying irrigation by turns.

The advantages of such a system are many. By concentrating the available supply in half, or a third, or a less fraction of the canals, and giving the whole of it to the section whose turn it is to take water, the irrigation is made easy in consequence of the higher water levels produced in the canals. At the same time, in the other sections which are not receiving water, the danger of the canals causing waterlogging of the soil is removed, as they are either empty or flowing at a low level. The crops require water at certain intervals, and not continuously. It is better for them, as soon as they have received a watering, that the water supply should be shut off from their neighbourhood, so that all excess of water, over and above that used up or absorbed, may be got rid of, and not be allowed to stagnate. Irrigation by rotation, moreover, is a system that conduces to economy of water. For the water is delivered just where and when it is wanted for irrigation, and is therefore not allowed to run to waste. The loss from evaporation and absorption is less, as the water is spread out over a less extent of canals. The irrigation staff can superintend the distribution more thoroughly, as their exertions can be wholly devoted to the section under irrigation for the period of its supply. The cultivators also find such an arrangement a convenience, as they know exactly when they must arrange to water their fields. Moreover, the velocity of current of the canals, when in flow, is maintained at a high rate in consequence of the fuller

discharge, whereby more of the silt is carried forward to the fields and less deposited in the canal. Lastly, the system ensures an equitable distribution of the water to all cultivators, and offers such facilities for reducing the amount of waterings given in a season of short supply that the drawbacks of a deficient supply can be made to bear equally on all, with a minimum of disadvantage to anyone.

In India there are two modes of applying the rotation system. One arrangement is that in which all the distributing canals are kept in continuous flow, and the outlets, supplying the village channels, are opened and closed by turns. The outlets are grouped into two or more sections, and each section is allowed to take water for a certain number of days in its proper turn. The other arrangement is that in which the distributaries are subjected to rotation. As with the outlets, they are grouped into sections, and each section in turn flows with full discharge while the others are closed. Sometimes a combination of these two arrangements is adopted, and rotations are applied to groups of distributaries, and again to groups of outlets on those distributaries. "In the simplest cases, where only the outlets from the distributaries are *tatiled*, it is usual to divide the distributary into three lengths, so that the village channels taking off each length command areas which are approximately equal. The outlets in the first length of the distributary usually get water for three days in each week, and are closed for four days. The outlets in the second length of distributary are open on the four days when those in the first length are closed, and closed on the three days when the others are open; in the third length of the distributary the outlets to the village channels are allowed to be open all the week as a rule, and they absorb all the water passed on by the upper lengths" (Buckley).

When the distributaries are subject to rotation, the programme has to be drawn up to cover longer periods, and it becomes more complicated. The recent history of irrigation

in Egypt furnishes a good example of this alternative method of applying the rotation system.

In Egypt the severest application of the system of irrigation by turns was made in the summer of 1900, when the scantiness of the available water supply, in relation to the requirements of the cultivated area, exceeded all previous and subsequent experience. The irrigation officers were faced with this problem. There was a certain area of land under cotton which had to be irrigated; there was an insufficient and constantly diminishing supply with which to irrigate it. The Assuan reservoir was not as yet in existence. The crop, that was in danger of suffering for want of timely irrigation, was cotton, on which the wealth of modern Egypt principally depends. The cotton plant, during the season of low supply in summer, requires watering at intervals of eighteen days. It is generally believed that the yield is diminished if the intervals between waterings are prolonged beyond eighteen days. But, in the summer of 1900, there was not enough water in the river to complete one watering of the whole cropped area in so short a period. There were then only two possible alternatives to choose between: either the area of crop to be irrigated must be reduced to that which the discharge was capable of watering in eighteen days, or a longer time for the watering must be allowed. The practical impossibility of reducing the crop area, once it had been planted, without doing injustice to individuals, caused the rejection of this alternative. It, therefore, remained to arrange a programme by which sufficient time should be allowed for the irrigation of the whole area of cotton crop. A given discharge takes a definite time to irrigate a given area, and, as the discharge decreases, the time of the operation must increase; that is, in other words, the intervals between the waterings of any particular field must be longer. It was found a convenient arrangement to divide each separate system of canals into three sections, which were designated A, B, and C. Now much of the irrigation was effected by pumps, which, it was calculated,

could complete the irrigation of all the crops depending on them in six days, but not in less. So six days was accepted as the period of working for each section. If the water supply had been sufficient to irrigate the whole cropped area in eighteen days, each section would have taken water in turn for six days, and have been prevented from taking it for the succeeding twelve days; that is, the interval between waterings for any particular field would have been eighteen days. But it was found that the supply was only sufficient at first to give one watering in twenty days, and later on in twenty-four days, and still later, at lowest supply, in twenty-eight days. To arrange for the twenty-eight days' rotation, it was necessary to rearrange the subdivision and to group the canals into four sections, which were called D, E, F, and G, to avoid confusion with the threefold arrangement. The programmes of rotation were, then, made out on the following basis:—

Three Sections.	One watering in 20 days.	One watering in 24 days.	
Section A takes water . .	6 days	6 days	B and C stop.
General stoppage . . .	1 ,,	2 ,,	
Section B takes water . .	6 ,,	6 ,,	A and C stop.
General stoppage . . .	1 ,,	2 ,,	
Section C takes water . .	6 ,,	6 ,,	A and B stop.
General stoppage . . .	...	2 ,,	
	20 days	24 days	

Four Sections.	One watering in 28 days.	
Section D takes water . .	6 days	E, F, and G stop.
General stoppage . . .	1 ,,	
Section E takes water . .	6 ,,	D, F, and G stop.
General stoppage . . .	1 ,,	
Section F takes water . .	6 ,,	D, E, and G stop.
General stoppage . . .	1 ,,	
Section G takes water . .	6 ,,	D, E, and F stop.
General stoppage . . .	1 ,,	
	28 days	

The general stoppages of one or two days were intended to provide for the filling of the channels of the section whose turn to work came next, so that the water might reach the tail ends of the sections, and the pumps at the tails have as good a supply from the commencement of their six-days period as those higher up the canals. These intermediate general stoppage days were also used to give water to those who had been badly supplied during their proper working period. It was moreover arranged that, if the tail reaches of any section did not get water in their proper turn, they should be given water with the section whose turn came next. By so arranging, it became possible to get water to them, since all the pumps or heads above them on the same branch were stopped. The intermediate days of general stoppage provided a reserve which could be utilised to prevent arrears accumulating to such an extent as to upset the published programmes and introduce confusion during the most critical period.

In the summer of 1900, in Egypt, the supply was so short that, if the cotton crop was to be saved, provision could not be made for rice irrigation, and as the rice crop in comparison with the cotton crop was of little importance in both extent and value, it was sacrificed to the needs of the more valuable crop. By such measures as described, the cotton crop was irrigated by a discharge of 21 cubic metres a day per acre, instead of the normal 30 cubic metres a day which is the discharge required to allow for waterings being given every eighteen days. The latter is the "accepted duty," as has been explained in Chapter III.; the former represents the actual work done by the water in the summer of 1900. According to the accepted "duty," 1 cubic foot a second should irrigate $81\frac{1}{2}$ acres; in the summer of 1900, 1 cubic foot a second was made to irrigate 116 acres, or more than 42 per cent. in excess of the "accepted duty." But, under these circumstances, some of the crop suffered in yield from insufficiency of water, and so the season's apparent "duty" included duty imperfectly performed in

consequence of the water having been called upon to do work beyond its powers.

After the experience of a succession of low summers in Egypt, the conclusions arrived at, as to the best programme for rotations, is thus stated in the Irrigation Report of Egypt for 1902:—"As a consequence of previous experience, it has been decided in 1903 to adopt the three-section arrangement of distribution, by which each section takes water in turn for a third of a full period, which has been fixed at eighteen days; so that each section will get water for six days, and be without it for twelve. For canals, however, from which rice is irrigated, two sections are adopted, each section working for four days and stopping for five. The day when neither section works comes after the working of the first section, and is utilised for filling the channels of the second section before water is drawn off from them. As the rice full period is half of the cotton period, a cultivator may, if he likes, raise cotton or rice, or both. Supposing he has an area of 200 acres to put under crop, he can put it all under rice and irrigate it once in nine days; or he can put it all under cotton and irrigate 100 acres during one turn and 100 acres during the next, so that one watering in eighteen days is given to it all. Or he may put 100 acres under rice and 100 under cotton. In this case he would irrigate all the rice and 50 acres of cotton during one turn; and all the rice again and the other 50 acres of cotton the next turn: so that, in every case the rice would get a watering in nine days, and the cotton in eighteen days. The cultivator is thus free to plant what he likes."

This programme contemplated assistance from the Assuan reservoir, which had been completed in 1902. Without such assistance, the period of eighteen days would have had to be increased to twenty-one, and later to twenty-four, days by inserting one or two days of general stoppage between each section's period of working, as was done in 1900. With a period of nine days between waterings of rice, and of eighteen

days between waterings of cotton, the discharge required at the canal head was found to be at the rate of 30 cubic metres (1060 cubic feet) a day per acre of cotton crop, and at the rate of 60 cubic metres for rice. If the supply falls short of these allowances, there are, as has already been stated, only two ways of meeting the deficiency of supply, namely, either by lengthening the intervals between waterings or by reducing the area of crop to be watered. The former is sometimes the only practicable alternative.

If the other alternative of reducing the area of crop is adopted, the reduction must be determined upon before the crop is sown or planted. Sir Colin Scott-Moncrieff, in his address at the Meeting of the British Association, 1905, already quoted, thus describes the system of distribution under the "Irrigation Association West of the Sesia," in Italy: "To effect the distribution of the water the area irrigated is divided into districts, in each of which there is an overseer in charge and a staff of guards to see to the opening and closing of the modules which deliver the water into the minor water courses. In the November of each year each parish sends in to the direction-general an indent of the number of acres of each description of crop proposed to be watered in the following year. If the water is available the direction-general allots to each parish the number of modules necessary for this irrigation; but it may quite well happen that the parish may demand more than can be supplied, and may have to substitute a crop like wheat, requiring little water, for rice, which requires a great deal."

In certain districts of India it is considered desirable to restrict the area under irrigation to a certain proportion of the area commanded. When the available supply of water is insufficient to irrigate the whole cultivable area commanded, such a restriction is desirable for the sake of distributing the water to as many parts of the district as possible for the benefit of the people. But there is another reason for the

restriction. If irrigation is spread over all the area commanded, the soil, when light, is liable to become water-logged, and the spring levels may be unduly raised.

In the discussion on the Irrigation Papers read at the International Engineering Congress of 1904, at St. Louis, Mr. J. E. de Meyier describes the system of rotation, or *golongan* system, as practised in Demak, Java: "The fields are divided into four, five or six classes: those of the second class get the water a week later than those of the first; those of the third a fortnight later, and so on." Mr. de Meyier gives the following example to explain the system, taking a quick growing kind of rice as the crop of his illustration. "The rice fields are under irrigation for nineteen weeks. For the first two weeks of this period the discharge required for the preliminary operation of ploughing is at the rate of 1 cubic foot a second for every 50 acres. After the ploughing the rice is sown on about a tenth of the area to form nurseries for the seedlings, which will afterwards be transplanted to cover the whole area. The nursery period lasts five weeks, and during this time the discharge needed is at the rate of 1 cubic foot a second for every 50 acres of nursery area, with an addition of 1 cubic foot for every 2,000 acres of the whole area to allow for further tilling operations. After transplanting the seedlings to the larger area, an increased supply at the rate of 1 cubic foot a second to every 150 acres for a week, and then at the rate of 1 cubic foot a second to about every 80 acres for three weeks, is required; and thereafter a gradually diminishing supply till the nineteenth week. If then, for instance, the total area of the rice fields is 10,000 acres, and if the whole of it is taken in hand at once, the discharges required will be those represented by the figures of the second column of the accompanying table. Now supposing the river from which the supply is drawn never discharges more than 95 cubic feet a second, and that it continues to flow, though with diminishing volume, for, say, twenty-five weeks, how are the 10,000 acres of rice crop to be

irrigated under these conditions, seeing that for seven weeks out of the nineteen a greater discharge than 95 cubic feet a second appears, from the figures in the second column of the table, to be necessary? The method of solving the problem is this: The 10,000 acres of rice field are divided into five sections, A, B, C, D, and E, of 2,000 each. For the first two weeks sections A and B get the full discharge required for the preliminary operation of ploughing, and the other three sections are left alone. In the third and fourth weeks sections C and D, and in the fifth and sixth weeks section E, get in their turn the full discharge required. For the five weeks succeeding the ploughing, each section successively gets the reduced supply required for its nursery, and after that an increase when the seedlings are planted out, followed by a decrease as the plant becomes mature. But in sections D and E the nursery stage has to be prolonged to six and seven weeks respectively on account of the limited supply not admitting of an increase at the end of five weeks."

"The table on the next page shows this method of overlapping, whereby it is arranged that the total discharge required at any time never exceeds the river discharge of 95 cubic feet a second. The figures in the last column give the aggregate daily discharges required by the five sections, week by week, for the twenty-five weeks of the rice-cultivating period."

As a contrast to systems of rotations which have been devised to do equal justice to all concerned, the custom of "priorities" of the United States is worth notice. The law recognises the prior right of first comers to be first served with the water of running streams to the extent to which they put it to profitable use. The man who first made use of the water of any stream to cultivate a certain area is, by custom and law, entitled to withdraw the same quantity of water when his land requires it, without regard to the interests of his neighbours. The man who followed him, at no matter what interval of time, has a

secondary right, and may in future withdraw from the stream the amount of water originally used to cultivate his farm, provided there is sufficient to first supply the prior settler. The man who is third in point of time can utilise his share only

Number of Week.	Supply in Cubic Feet per Second.						Aggregate Supply Required.
	The whole Area of 10,000 Acres at once.	The Area divided into Five Sections of 2,000 Acres each.					
		Section					
		A.	B.	C.	D.	E.	
1	200	40	40	—	—	—	80
2	200	40	40	—	—	—	80
3	25	5	5	40	40	—	90
4	25	5	5	40	40	—	90
5	25	5	5	5	5	40	60
6	25	5	5	5	5	40	60
7	25	5	5	5	5	5	25
8	80	16	16	5	5	5	47
9	120	24	24	5	5	5	63
10	120	24	24	16	5	5	74
11	120	24	24	24	16	5	93
12	100	20	20	24	24	5	93
13	100	20	20	24	24	5	93
14	75	15	15	20	24	16	90
15	75	15	15	20	20	24	94
16	50	10	10	15	20	24	79
17	50	10	10	15	15	24	74
18	25	5	5	10	15	20	55
19	25	5	5	10	10	20	50
20	—	—	—	5	10	15	30
21	—	—	—	5	5	15	25
22	—	—	—	—	5	10	15
23	—	—	—	—	—	10	10
24	—	—	—	—	—	5	5
25	—	—	—	—	—	5.	5

after the first and second men have had their prior claims satisfied; and so on, the late comers being compelled, if necessary, to leave the water untouched until all with prior rights have had the full quantity which is their legal due. As the country develops under the stimulus of irrigation, there is a growing tendency to abandon the observance of priorities, and

to adopt the principle of distribution according to areas of crop or cultivated land.

When the delivery and distribution of a water supply is effected by an artificial system of canals, it is usual to charge for the irrigation by water rates in some form or other. In Java, however, there is no water rate or charge for water. The rainfall of the island is considerable, and it would be difficult to estimate to what extent a full supply from canals benefits the crops which hitherto had depended mostly on rain assisted by a scanty allowance of irrigation water. The land tax is assessed in relation to the average yield of the crops grown, which depends on the fertility of the soil and the nature of the water supply. When the water fails, a partial remission of the tax is allowed. The land tax assessment and collection thus takes account of the irrigation supplied, and no additional water rate can be levied.

In Egypt also there is no Government water rate. Payment of the land tax confers the right to a supply of water sufficient for the maturing of one crop during the year, and imposes on the Government the obligation to make that supply available. If the Government fails to do so, the land tax is remitted. The only measurements made are of those areas which have remained without water throughout the year from no fault of the cultivator, and on which the land tax has, therefore, to be remitted. The irrigation officers of Egypt are thus relieved of all the troublesome revenue work which adds so much to the duties of the irrigation staff in India.

The rates charged in India for the water required to mature a crop vary from 1 rupee an acre for rice to 20 rupees an acre for sugar-cane. The average rate for the whole of India is rather more than 3 rupees an acre for the revenue realised, and in addition 1 rupee an acre for working expenses. Compared with the value of the crops raised by irrigation the water rates charged in India, if not low, are decidedly moderate. But in India as

a rule the crops are not wholly dependent on the canals, as, to a varying extent, rainfall supplies the water needed. The water rate may therefore be considered to be made in return for a guarantee that sufficient water shall be supplied to ensure the maturing of the crop. But in Sind, where crops are grown only on irrigated land, and where land without water is valueless—the conditions being much the same as in Egypt—there is no separate charge for irrigation. As in Java and Egypt, the assessments of the land revenue are made on the basis of the average produce, and account is thus taken of the increase of yield due to irrigation. This system of a "consolidated" rate is followed also throughout the Madras Presidency, in certain districts of Burmah, and also in some parts of Bombay depending on old irrigation works.

In the Western States of America, where the rainfall is less than 20 inches per annum, a water rate is charged of from £2 8*s*. to £4 per acre, the farmer paying in addition a rate of from 2*s*. to 10*s*. per acre annually for maintenance. In comparison with India these rates appear high.

In Piedmont in Italy the farmer pays, according to the area he waters, his share both of the sum which is due to the government and of the cost of maintaining the irrigation works. The Government charge per annum is at the rate of 800 liras per module of 2·047 cubic feet per second delivery, or £15 12*s*. 7*d*. per cubic foot per second.

In France the association or syndicate that manages the canals charges a water rate on the basis of a continuous flow of 1 litre per second per hectare. The rate varies from 35 to 70 francs per annum per hectare, equivalent to 12*s*. to 24*s*. per acre.

In Spain the price of water varies considerably. The followers of the conquerors who expelled the Moors pay nothing for the irrigation works that serve the lands granted to them in reward for their services, excepting only a small annual tax to cover the cost of maintenance. The same

privilege is enjoyed by all the land-holders of the irrigated plain of Valencia, "according to what had been anciently established and practised from the times of the Saracens." Otherwise irrigation is paid for either by the year or for a single watering. The price of a single watering—reckoned as consuming 180 to 200 cubic metres per acre—varies in Alicante from 10*d.* to 21*s.* an acre; in Lorca the price is 10*s.* an acre, in Almansa 1*s.*, in Granada 1*s.* 8*d.* to 3*s.* 5*d.* When irrigation is paid for by the year, the annual charges are as follows: in Catalonia, on an average, 11*s.* 2*d.* an acre; on the canal of Urgel and at Malaga 19*s.* 3*d.*; on the Esla canal £1; and on the Henares canal £1 9*s.* The wide range in price for a single watering in Alicante is due to variations in the amount of the available supply and in the dryness of the season.

In countries where the agricultural classes are for the most part little educated, it is best for all interests that the control of the irrigation should be in the hands of the Government. In Egypt and in the British possessions in India irrigation is so administered. The responsibility for the construction of the canal works, and for the just and economical distribution of the water, rests with supervising officers of the higher grades in the irrigation service. On the character and ability of these officers depends the successful and satisfactory working of Government irrigation systems. In India and Egypt this condition of success has not been wanting ever since British engineers have been the responsible officers.

The duties of the Government irrigation engineers are manifold. They elaborate the project for the irrigation of a tract of country, and design the works of supply, distribution and drainage; they arrange for and superintend the construction of the works; and, lastly, they control the water distribution of the completed canal system, and the assessment of the water revenue derived from its working. As part of the irrigation system the flood banks of the river are in their

charge, to be maintained as a defence against inundation of cultivated land. Associated with the maintenance of flood banks, training works for the control or improvement of a river have often to be undertaken. Inland navigation, whether on natural waterways or on artificial channels, falls under the care of the irrigation officer, at any rate in India and Egypt. Land reclamation by drainage works and by pumping may also be added to the list of his duties. In India he may even be called upon to do magistrates' work, and try cases and sentence offenders under the Irrigation Act.

The Irrigation Branch of the Public Works Department in India is thus constituted: A chief engineer is at the head of the establishment of the province; under him are superintending engineers of "circles," who have jurisdiction over areas including 500,000 to 1,000,000 acres of irrigation: next come the executive engineers, who control "divisions," comprising sometimes 200,000 acres of irrigation. The executive engineer is the officer who is responsible for the proper assessment of the irrigation revenue; it is his duty also to arrange for the repairs of the works, to prepare projects for the improvement of his division, and to secure the proper regulation and distribution of the canal water. He is assisted by a large establishment of Government officials, chiefly composed of natives of India, who live in the various "sub-divisions" and "sections" into which the division is divided.

In Egypt the Irrigation Department is a branch of the Public Works Ministry, which is under a minister, assisted by an under-secretary of state. The irrigation service is under two inspectors-general, one for Upper Egypt, and the other for Lower Egypt. Under the inspectors-general are inspectors of irrigation, and under them again directors of works and surveyors of contracts, and chief and district engineers. Each inspector-general's charge comprises from 3,000,000 to 3,500,000 acres of irrigated land. The inspectors of irrigation have charge of "circles," comprising areas of 500,000 to 1,000,000 acres.

There are, however, besides the "circles," directorates of about 200,000 to 300,000 acres, with directors of works in charge. The duties of an inspector of irrigation in charge of a circle are, if not the most important, at any rate the heaviest of all.

Java is in a transition stage as regards methods of administration in irrigation matters. Experimental establishments, regulations and methods of distribution do not seem as yet to have led to any definite conclusions as to what is the best to adopt. The general idea on which the experiments are based is to divide the island into fourteen irrigation circles, each of which would contain the entire catchment basin of one or more rivers, irrespective of the political frontiers of the provinces. Each circle would be put in the charge of an engineer with a proper staff. The circle engineers would be under the chief engineer, who is the head of the public works division, and they would be the technical advisers of the residents and their provincial officers. The experimental organisation of the Javan irrigation service has points of resemblance to the administrative arrangements of both India and Egypt.

Though it may be best for countries with native agriculturists, such as those of India and Egypt, to have their irrigation administered by Government, it does not follow that there is not a better way for countries with an agricultural class more advanced in civilisation. A good example of self-government in irrigation matters is given by Sir C. Scott-Moncrieff in his British Association Address, already quoted from more than once. He describes how these things are managed in Piedmont, in Italy: "The Irrigation Association west of the Sesia takes over from the Government the control of all the irrigation lying between the left bank of the Po and the right bank of the Sesia. The Association purchases from the Government from 1,250 to 1,300 cubic feet per second. In addition to this it has the control of all the water belonging to private canals and private rights, which it purchases at a fixed rate. Altogether it distributes about 2,275 cubic feet per second, and irrigates

therewith about 141,000 acres, of which rice is the most important crop. The Association has 14,000 members and controls 9,600 miles of distributary channels. In each parish is a council, or, as it is called, a *consorzio*, composed of all landowners who take water. Each *consorzio* elects one or two deputies, who form a sort of water parliament. The deputies are elected for three years, and receive no salary. The assembly of deputies elects three committees—the direction-general, the committee of surveillance, and the council of arbitration. The first of these committees has to direct the whole distribution of the waters, to see to the conduct of the *employés*, etc. The committee of surveillance has to see that the direction-general does its duty. The council of arbitration, which consists of three members, has most important duties. To it may be referred every question connected with water rates, all disputes between members of the Association, or between the Association and its servants, all cases of breaches of rule or of discipline. It may punish by fines any member of the Association found at fault, and the sentences it imposes are recognised as obligatory, and the offender's property may be sold up to carry them into effect. An appeal may be made within fifteen days from the decisions of this council of arbitration to the ordinary law courts, but so popular is the council that, as a matter of fact, such appeals are never made."

In Spain there exists a parallel to the Piedmont method of administration. The irrigation syndicate of Valencia was the first "tribunal of waters" to be created specially for the trial of irrigation cases. It sits in the open air, upon the porch of the side door of the Cathedral, and settles all questions relating to irrigation that are brought before it. There is no appeal against its decisions. The institution, which is of Moorish origin, is very popular in Spain, and has been imitated, with more or less success, by all the other syndicates of the country.

The regulations concerning the granting of irrigation

concessions in Spain contain a condition which is worthy of special note. The prospective irrigators are bound to form a syndicate among themselves, even when the water supply is conceded to a company which is authorised to recoup itself for its outlay by levying an annual payment for a fixed number of years. The syndicate, on the one hand, is better able as a body to protect its own interests in its dealings with the company than individuals would be; and, on the other hand, the company's relations with the irrigating community are facilitated by their having a duly recognised body of representatives to deal with.

The system of canal management in France is in some repects similar to that of Spain. None of the canals of Southern France belong to Government. With the exception of the case of the Marseilles Canal, the usual agency by which canals are constructed and administered is an association of cultivators. The desire of the French Government is that those who use the water should organise themselves into associations, or syndicates, with authority to construct and work irrigation canals at their own risk. The Government aids the undertaking by contributing about one third of the estimated cost of the work, and supervises the work as far as it considers necessary.

In America no well-devised scheme of canal administration has as yet been evolved, but there is a tendency to admit the necessity for public control of irrigation. The pioneer settlers, when they first made use of the water of a running stream for irrigating their land, were not under the restraint of any regulations as to the time of opening and shutting the head-sluices, but pleased themselves about it. When the needs of others compelled the introduction of some management of the water supply and the drawing up of regulations as to its use, the farmers, who inherited from their pioneer predecessors their habits of freedom to do as they liked, were slow to submit to the imposed restraint. When application to the law courts failed

in its effect, the irrigator, who was deprived of his supply of water through illegal use of it by someone higher up the stream, had no other course left open to him but to shut down the offender's head-sluice by force. Mr. Elwood Mead in his paper read at the International Engineering Congress, 1904, gives an example of such a case. A canal owner in California was asked how he managed to protect his rights in the seasons of shortage; he replied that, in the first place, he had obtained a decision establishing his legal title to water; but that, in addition, every year he shipped in two men from Arizona who were handy with a gun, and that between the courts and the guns he managed to get his share. To which Mr. Mead adds this comment: "Peace and prosperity for the individual and the community alike depend upon public control of the streams and the enforcement of laws by men of experience and administrative ability of a high order. The greatest weakness of American irrigation has come from the failure to recognise this." Six States have, however, introduced government administration of canals, but the systems differ so widely from one another that a general description applicable to all cannot be made. Still, the policy of one State may serve as an illustration. According to the Wyoming code, the water of canals, streams, springs, lakes and ponds is State property. The State Engineer is the president of a board of five men managing this property. The State gives irrigators free use of the water, permits for this being issued by the State Water Board. It is a misdemeanour to take water without such a permit. To secure it intending users of water must file a map and description to show the position of the proposed channel or reservoir and the land to be irrigated. Permits are refused for any project which would cause injury to an existing right. But when permits are granted, after the water has been actually applied to the land, the State issues a certificate of appropriation which describes the land in question. These certificates are recorded in the same manner as land laws. In

order to protect the rights thus bestowed, the State has to control the distribution of the water when there is not enough for all. For this purpose the State is divided into four divisions, and these are sub-divided into forty districts. Each district has a water commissioner, a State official acting under the direction of the State engineer. In times of deficient supply he raises and lowers the gates in such a manner as to give each channel its proper share. Head-gates adjusted by the commissioner may not be moved by the owner. The commissioner has authority to arrest offenders, or he can call on the sheriff to do so. As Mr. Mead remarks, it is always difficult to induce irrigators to submit to this public control, but, once adopted, it is always maintained. It relieves irrigators from watching their neighbours. They do not have to patrol the stream at night to prevent gates being raised when they should be closed. Where irrigators have to defend their own rights, neighbours are always at war. Where there is public control they live in friendly relations with each other, while the water commissioner is often abused. If he does his work with tact and justice, he becomes the most important member of the community, and contributes to its respect for law and order, and to the peace of mind and well-being of the irrigators to a degree which has to be experienced to be understood.

Those who have had experience of irrigation in Egypt during the last twenty years will understand these remarks well. Before a real control was exercised over the distribution of water by engineers of experience and honesty, the native irrigators, during the period of water scarcity, used to settle among themselves all irrigation questions by breaking each other's heads with *nabouts*, a stout stick of a kind convenient for the purpose. When the inspector of irrigation (corresponding to the water commissioner of America) assumed effective control of the working of the canals, the summer death-rate due to water disputes declined, and, before long, perfect confidence in the inspector's justice and ability was established.

It is seldom now that any agriculturist in Egypt in want of water takes the law into his own hands.

But before all else, as a preliminary to any scheme of canal administration, the right of the public to the natural water supply of the country must be safeguarded against any exclusive appropriation by individuals. This important duty should not be neglected or postponed by the Government of any country that is endowed with the means of development that irrigation brings. Rivers, torrents, streams, and all natural watercourses, and the water that flows in them, should be declared by decree to belong to the public domain. In Italy and Spain the example has been set for other countries. In India and Egypt no one would think of contesting the Government's right to possess the country's natural waterways. According to the Wyoming code in the United States, which served above as an example of State administration, the water of canals, streams, springs, lakes and ponds is made State property. France has stopped short of a thorough-going State policy in respect to the ownership of its watercourses: for, though irrigation is indispensable in the south of France, it is not so in Northern and Central France. The country as a whole is more interested in navigation than in irrigation. Consequently the waterways that are navigable by boats or rafts, whether natural or artificial, are declared to be the property of the State. Other watercourses belong to no one, but the riparian owners of land have the right of using the water. Nevertheless the Government exercises a supervision over all these waterways, and no water can be taken for purposes of irrigation without a special permit signed by the prefect of the department.

Sir William Willcocks, in his Report on "Irrigation in South Africa, 1901," lays stress on the necessity of establishing by decree that all rivers and natural watercourses are part of the public domain. The longer this action is postponed the greater will be the difficulty of taking it, as vested interests to

be overcome will grow in number and strength with the development of the country. More especially is it necessary to take this step in South Africa, as the only possible means of promoting the agricultural development of the country seems to be by means of water storage; and, if water storage is the solution of the agricultural problem, Government must undertake the work. The construction of dams and the formation of reservoirs with their distributing canals are undertakings too vast for private enterprise, and they affect the prosperity of so wide an area that the State should assume the responsibility for their construction and subsequent management.

CHAPTER XI.

FLOOD BANKS AND RIVER TRAINING.

If perennial irrigation is given to lands which have hitherto been subject to inundation from the flood of a river, the crops that will thereafter be standing on the ground during the flood season must be secured against submersion by the construction of protective banks. As the deltas of rivers are formed by the deposit of recurring floods, the highest land so formed cannot be above the reach of a maximum flood. Consequently, when a river delta is brought under perennial irrigation, it is necessary to protect it by making river banks to prevent the floods from spilling sideways and flowing across country. Most of the canals of Upper India and those of Egypt serve deltaic tracts, and consequently river banks are an essential feature of their canal systems. But the confinement of the flood discharge to the main channel or channels of the river is interfering with the natural process by which the land level has been hitherto gradually raised, so that henceforward the raising of the land surface will, if it does not altogether stop, proceed at a much slower rate than in the past. At the same time the amount of silt carried by the river and deposited at its mouth, where it meets the sea, will be at least as much as before, and the rate at which the river bed will rise in consequence of the yearly increasing deposit will remain undiminished. The river bed will, therefore, rise at a more rapid rate than the land surface alongside it, and with it also the heights of floods. Consequently it will be found necessary from time to time to add to the height of the flood protective embankments, which may thus, after a sufficient period, become inconveniently high. It has been calculated from the evidence

of ancient monuments that the lower portions of the Nile Valley and its delta have been raised by the natural action of the river at the rate of 4 inches a century. If, in consequence of the construction of Nile banks on perennial irrigation being introduced in the delta, the further raising of the land surface has been stopped while that of the river bed continues, it will be found a thousand years hence that the crest of the banks, if maintained at the same height above highest flood as is the rule to-day, will have to be 3 feet 4 inches, or a metre higher than they are now above mean sea level.

There is another respect in which natural arrangements are upset by the construction of river protective banks. When artificial control is absent, the flood in the river branches of a delta finds its way to the sea not only along the main channels, but also by spill channels along which part of the river discharge flows at high flood. Below the take-off of each successive spill channel there is a decrease in the discharge which the main channel has to carry. Consequently the discharging capacity of the river channel, which adapts itself to the work it has to do, constantly diminishes from the head to the tail. Now, when these spill channels and all side escapes for the flood water are closed by river protective banks, the whole flood discharge will flow forwards along the proper channel of the river; and, since the dimensions of the channel diminish towards the tail, the flood levels in the lower reaches will rise higher, relatively to the land alongside the river, than they did before the spill channels were closed, necessitating the raising of the flood embankments to contain the floods. This consideration will affect the question as to how far down the river branches it is advantageous to extend the river banks and to prevent the river spilling sideways.

In the delta of Egypt the level of a high flood in one of the branches is from 3·0 to 3·5 metres (about 10 to 11½ feet) above country level. These levels are attained in the middle third of the Damietta branch. At the head of the branch the height of

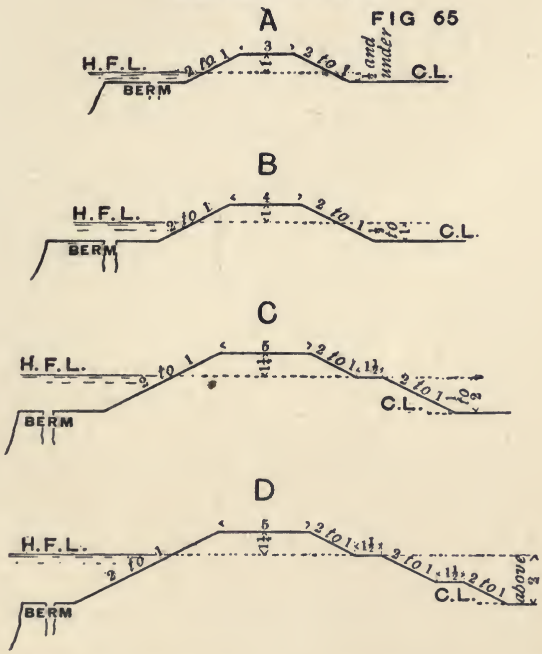
an extreme flood above country level does not exceed 2 metres (6½ feet). At Damietta, 15 kilometres above the meeting with the sea, the flood falls to country level. The dimensions, adopted of late years, for the Nile banks of Lower Egypt are shown in Fig. 65.

Fig. 65 A gives the section when the high flood level is not

NILE BANKS

Dimensions in Metres

FIG 65



more than half a metre above the country level inside the banks. If the soil is sandy, the crest width is increased to 4 metres. The same crest width of 4 metres is also given to the bank if it is used as a road.

Fig. 65 B gives the section when the high flood level is over half a metre but not more than 1 metre above the country level. If the bank is used as a road, the crest width is increased to 5 metres.

Fig. 65 C gives the section when the high flood level is over 1 metre but not more than 2 metres above country level; and Fig. 65 D when it is over 2 metres above country level.

If infiltration takes place to any considerable extent the lower slopes of the bank on the land side are made three to one, or even flatter, as experience may show to be necessary. If the soil is very sandy, it is better to make the slopes three to one and to omit the land side berms.

In India, America and, in fact, most countries, the slopes of the banks are always turfed; but in Egypt they are left bare, for the very good reason that there is no grass for turfing to be found, and there is no rain to keep grass alive if grown from seed.

In America flood embankments are termed "levees." The usual dimensions for a levee in the United States are 8 to 10 feet of crest width and slopes of 3 to 1. If the soil is sandy the top width is sometimes made 15 feet and the slopes 5 to 1. If the bank is high, a berm about 20 feet in width is added on the land side, some 8 feet below the top of the levee, and the slope of the bank below the berm is made flatter than the slope above.

In Italy, the Po embankments have a crest width of from 23 to 26 feet, sometimes reduced to 16 feet. The side slopes are formed at 2 to 1 or 3 to 1. There are usually two berms on the land side.

On the Rhine, the river banks have a top width of only 6 or 7 feet, which is doubled when the crest is utilised as a road. The slopes are made 3 to 1.

In constructing flood embankments the precautions taken to ensure safety vary considerably in different countries. It is remarkable what a simple matter the construction of a bank is in Egypt, and what few precautions are taken. The banks are thrown up without any special preparation of the land surface on which they are to be made; the soil is not deposited in layers, nor watered, nor rammed. The large clods are broken

up, and the excavation pits are kept at a certain distance from the outside toes of the finished bank. But this is all. And yet there is no rain to consolidate the new earthwork, nor is there turf to protect the slopes. The banks do not breach, at any rate from the pressure of water. If they did breach for want of more elaborate methods of construction, more precautionary measures to obtain security would by now have been introduced. Probably the dimensions given to the banks in Egypt are sufficiently liberal to dispense with the methods of construction which are imperative with banks of comparatively slight section.

When a breach occurs it is almost always, if not always, found to be due to causes other than that of direct water-pressure. Some soils become waterlogged and lose their power of supporting weight. When this happens below a high bank subject to a considerable head, the soil supporting it may give way and cause a subsidence of the bank, sufficient sometimes to allow the water that is being retained to flow over the top of the bank and breach it. In such cases it is better to spread the weight over a broad base by giving the bank flat slopes or frequent berms, and also to keep the borrow pits at a safe distance, so that the natural soil may remain intact to resist settlement.

Sometimes wave action may cause a breach, if a bank is left at its mercy without protection. But this seldom happens; and when it does it is due to negligence on the part of the watchmen whose duty it is to guard the bank. For the erosion effected by waves is more or less gradual, and the attack being made at water surface can be combated and successfully resisted if adequate means have been provided to meet such a danger. Light poles, or bamboos, and bundles of long grass or maize stalks, or any such material that happens to be obtainable in the neighbourhood, should be collected on the banks before the flood season, ready for use as required.

A fruitful source of danger is the existence of ill-constructed

culverts made in the banks to irrigate land immediately inside them. Such works should never be allowed unless they are built to an approved design and under the supervision of Government officers or responsible representatives of the public who are interested in the safety of the banks.

There is one other and more formidable danger to which river banks are subject. The most frequent cause of breaches is the undermining action of the flowing river along reaches where the soil of its margins is light and the velocity of its current high. If precautions to meet this danger are postponed till the flood has come, the chances of successfully meeting it are slight, except at ruinous expenditure. If the river embankment is close to the river edge and the river in flood begins to undermine it, it is often lost labour and material to throw stone into the deep water, or drive in stakes along the river front, while the cutting action goes on below the foot of the stakes. If there is danger of a breach, the only safe thing to do is to quickly throw up a retired bank at some distance behind the threatened length, so that it may take up the duty of protecting the country from inundation in the event of the original bank being breached. While the safety bank is being made, the river attack on the original bank must be held in check and its advance delayed by the best means available under the particular circumstances of the case.

It is, however, much safer and more economical to anticipate and guard against the danger of undermining during the low supply season that precedes the flood. There are two ways of doing this. The bank may be retired along the threatened lengths to a safe distance from the river edge beyond the reach of danger; or the points and lengths liable to suffer erosion may be protected by spurs and revetments of sufficient power of resistance to be relied upon. The latter method is adopted in the front of villages and wherever a retirement is impossible or objectionable. Otherwise the former method by retreat is generally preferable. But better than either method

is a combination of the two. The retirement of the bank from the river edge to a distance of about 50 yards, and the prevention of further encroachment by the construction of spurs, is the most satisfactory arrangement. The river bank would then be safe from any risk of being undermined, and its retirement would not have to be repeated in the future in consequence of further advances of the river. Spurs as a form of defence against encroachment are preferable to revetments of the slope, as they are more efficient and economical, and, when once established, require less attention than revetments. But as the eddy created down stream of a spur eats into the bank for a certain distance, this method cannot be adopted where the bank to be protected is not sufficiently retired from the river edge to be outside the limits of the eddy's action. In such a case the river-side slope must be protected by a revetment of stone or other suitable material which will offer sufficient resistance to prevent encroachment at any point.

The material used in the construction of river spurs and revetments may be stone, brick, brushwood, or any other suitable material that may be readily procurable. Stone or brick has the advantage of durability, and may therefore in the long run prove to be a more economical material to use than brushwood.

The forms given to spurs are various. The diversity is due, probably, to the different conditions existing at the places where spurs are found necessary. In India, a form much favoured is the T form, which has at its outer end a certain length of spur face parallel to the desired direction of flow, designed to guide the current. This would be an expensive arrangement if the spur were to extend into deep water.

In Plate V. is shown a form of spur existing in Spain. A timber gridiron, resting against a weighted tripod, forms a support for the smaller material, such as brushwood, by which the obstruction to the current is formed.

The usual form of spur adopted in Egypt has its axis inclined

at 120 degrees to the direction of the current. It has a sloping crest, commencing at the shore end from a point about 2 feet above highest flood level, and carried down to a point about 3 feet above low water level at the outer end. The slope of the crest, therefore, depends upon the length that it may be decided to give to the spur. Usually it is about 5 to 1. The crest width is made from 3 to 6 feet, and the side and end slopes are formed at 1 to 1. The spur is connected by an earthen "tie-back" with the river bank behind it, so that the flood may not take it in rear. The river side slopes immediately above and below the spur are revetted for short distances to protect the root of the spur from the action of eddies.

Similar spurs are also sometimes made for the protection of the sides of large canals which at full supply have a discharge of such volume and velocity that the side slopes suffer from erosion. Spurs intended for such a purpose are made in pairs, one spur on either side of the canal, and they are formed with their axes at right angles to the current. In other respects they resemble river spurs, but the position of the outer ends, and the slope to be given to the crest, are determined by considerations other than those that apply to river spurs. When the conditions of soil and discharge are such that the sides of a canal succumb to erosive action, the eroded material is carried forward by the water and spread about over the bed of the canal further down. Consequently when, as the season advances, the water level falls with a decreasing discharge, the obstruction to the flow, caused by the deposits of eroded material, seriously affects the available water supply. It is therefore important to prevent such deposits by stopping erosion. The proper distance apart of the opposing spurs of any pair depends on the discharges of the canal, the object being to produce and maintain a channel of uniform section and of such dimensions that it will carry its discharge without any scour or deposit taking place. A practical way of determining the width of bed to be allowed between the toes of

two opposing spurs is to study a longitudinal section of the bed made after a flood season, and so to discover the points at which the bed has remained at the correct level, having been neither lowered by scour nor raised by deposit below or above that level. Cross sections taken at these points will give the dimensions of the channel, adapted to the conditions of the canal, which it is desired to determine. The spurs should be constructed so that the waterway allowed at high flood levels between the opposing spurs of a pair may approximate to that of the selected cross sections; or be a little less, as the velocity of current must always be accelerated to a certain extent between the spurs if they perform the work of directing the flow. The interval between one pair and the next pair of spurs should be such that the effect of one pair shall begin where that of the next pair ends. Usually the distance would be from 200 to 300 yards. Experience of the actual working of such spurs on the four largest canals in Egypt has demonstrated that they are a most efficient means of checking erosion of the banks and of diminishing thereby the resulting deposits along the canal bed. The section of the canal is gradually restored by them to its correct width and depth, and the berms, which had been cut away, are reformed by a deposit of silt on the sides of the channel between the pairs of spurs.

River protective works, such as spurs to protect dangerous points against erosion, are different in their object from river training works. Canal spurs which are made with the object of stopping erosion, and also of producing a regular channel of uniform section, partake of the nature of both protective and training works. River protective works have usually to be made in the deep water which is to be found at threatened points; river training works are generally carried out in shallow water. The former, by strength of material, forcibly prevent the river from injuring its banks; the latter, by gentle persuasion, induce it to flow in the direction and behave in the manner desired.

River training works may be undertaken for different objects. They may be designed in the interests of irrigation, or of navigation, or for the purpose of reclaiming land; sometimes also for the sake of diverting the river channel from a too dangerous proximity to an important town, building or property of sufficient value to justify the expense involved.

It is often necessary to train the river for some distance up stream of the head works of a canal system, in order that the discharge may flow in a regular channel and correct direction as it approaches the weir or other river work of regulation. In India the river Ganges is trained above and below the Narora weir, at the head of the Lower Ganges canal, for 21½ miles, by works on both banks above the weir and on the right bank below it. The training works consist of groynes constructed in pairs at half-mile intervals, each groyne being tied back to the high ground, canal or parallel bank behind it, so as to confine the river discharge to the passage between the heads of the opposing pairs of groynes, and prevent any flow of flood water behind the groynes. The distance between the heads of the groynes is 3,000 feet, which is the normal width of the river. After groynes of various patterns and different materials had been experimented with, the type eventually adopted as the most efficient was the T-headed form, and the material employed was earth with rubble-stone facing and toes. The cross head of the T groyne was made 400 feet long, with an up-stream length of 300 feet and a down-stream length of 100 feet. The stalk of the T, or axis of the groyne, was placed at right angles, and the cross head parallel, to the direction of flow. Possibly, if the axes of the groynes had been placed at an angle with the current, the necessity for some, at least, of the up-stream 300 feet of the cross head would have been avoided. The works have been successful in training the river, but, like most training works, they have been costly to execute. As the heart of these groynes is earth, any serious settlement of the protective rubble toe and slope revetment would be followed by

the loss of the groyne, and the loss of one groyne would probably be followed by the loss of others down stream of it.

The type of spur already described under protective works as the favoured form in Egypt is made entirely of loose stone, the tie-back only being of earth. Consequently, if a settlement at the outer end takes place, it does not necessarily follow that the consequences are serious. It is in fact expected that newly-made spurs will settle for two or three years after their construction. If they do, they are repaired and made up to full section as often as the necessity arises, until at last, as the result of repeated settlements, the bottom stone reaches such a low level in the river bed that the scour of the current past the end of the spur no longer disturbs it, and stability is at length reached. A spur of this description can also be added to and lengthened by degrees after it has become established and stable, so that the effect on the river may be produced by a gradual process. Powers of persuasion and not of violence should characterise training works of discretion. Another virtue that the spur with sloping crest possesses is that the eddy produced down stream is of comparatively little violence, as the obstruction is presented to the flow in a gradually increasing form from the outer toe in deep water to the root of the spur where it rises above high flood level and unites with the tie-back.

In Egypt training works have been undertaken at the apex of the Delta to induce the river to bifurcate at the selected point, so that the twin channels may flow symmetrically on to the barrages which span the two branches, and in a direction at right angles to the face of either work. The training works consist of spurs to stop any encroachments taking place in a wrong direction, and to encourage them when they take a right direction; of revetments to preserve the river slopes which coincide with the sides of the ideal channels to be formed; and of a bar of anchored mimosa trees, renewed every year, across

the upper end of a side branch of the river which it is desired should close itself by a deposit of silt.

In Egypt, also, training works have been undertaken by a company with the object of reclaiming land in the bed of the river. The works, for the most part, take the form of a regulator at the lower end of a reach, the bed of which is to be reclaimed. By means of the regulator the flow is checked during the flood season, so as to produce a velocity most favourable to the deposition of silt. The bed level is raised by the deposit of successive floods until it is high enough to be cultivated. The silting up of side channels, for the object of reclamation, often effects an improvement in the navigable conditions of the river.

The deposition of silt behind spurs takes place more readily if the spurs are permeable than if they are impermeable. Spurs made of loose rubble are permeable so long as the interstices between the stones do not silt up; and this will only occur at the same rate at which the silt deposit forms down stream of the spur, to which there is no objection. Permeability is obtained sometimes by making the spurs of bushy trees or brushwood; and, in certain situations, such material is preferable to stone. But stone is the more durable, and if the action of the spur is to be continuous and to extend beyond a period of a few years only, it is to be preferred as the material of construction; unless practical considerations, such as the abundance of other suitable material close at hand, or the prohibitive cost of stone, call for its rejection. The existence of abundance of cotton-wood and willows on the Mississippi river determined the choice of material for the important training works undertaken in the interests of the navigation of that river. The aim of the engineers who direct the training works of the Mississippi is to obtain a uniform channel, and so to prevent alterations in the velocity of the current, to which is attributed the mischief of undermining banks and consequent shoaling. The object is the same as that for which spurs, as

already described, have been made in the large canals of Egypt, but the means employed are different. The cotton-wood and willows, woven into mattresses, are sunk in place and fixed along the sides of the channel to be regularised. For the protection of banks "mattress revetment is the chief method employed along the Mississippi and Missouri rivers. The brush grows in abundance, and in spite of continued denudation for these works the supply has not been exhausted, as cotton-wood and willows spring up rapidly, so that it is the cheapest material for use. Out of the abundance and cheapness of this material has grown the practice of its use, in connection with stone, also fairly plentiful, as a revetment for banks in this country (U. S. America)."[1]

[1] "The Improvement of Rivers," by B. F. Thomas and D. A. Watt.

CHAPTER XII.

AGRICULTURAL OPERATIONS AND RECLAMATION WORKS.

It has already been shown in Chapter III. that an irrigation engineer must acquire a correct knowledge of certain agricultural matters before he can estimate with any confidence the quantity of water that the canals will have to carry at different seasons. In fact the more complete his knowledge of such matters, the more competent will he be to design a project adapted to the needs of the land to be irrigated. The configuration of the ground, the nature of the soil, the description of the crops, the seasons of sowing and harvest, the times when water is needed, the habits of the cultivators, must all be considered when the "duty" of water for the prospective canal system is being determined. Again, when the financial results of any irrigation scheme are being calculated, it is not enough to include on the expenditure side the cost only of the canal and drainage works; but an allowance must be made for the sometimes considerable expense that the landowner will incur in preparing the ground for the application of irrigation. The ground may have to be levelled, or to be cleared of scrub or other growth; but, in any case, field channels, or ridges to divide the area into compartments or terraces for flooding, or other means for the internal distribution of the water, must be provided. The cost of these private operations will naturally vary with the conditions. M. Salvador, in his St. Louis paper on "Irrigation in France," states that it may be estimated at from 500 to 800 francs per hectare (£8 to £13 per acre). This estimate will appear exaggerated to those whose experience has been gained in countries where the agricultural conditions are peculiarly

favourable to irrigation, but those whose experience is of opposite conditions may reckon this estimate to be moderate.

In the preliminary stages of a project, information concerning the needs of agriculture, so far as irrigation is concerned, will be sought after by consulting the local farmers. But it must not be assumed that the cultivator's judgment as to what is best for his crops is infallible, when the conditions of farming, introduced by irrigation, are outside the limits of his experience. When the quantity of water obtainable is abundant and the farmer does not pay for it according to the actual quantity taken, he is apt to over-water his crop, and has to be taught by experience that, though water is a good thing, a crop may have too much of it. Especially is this the case if a deficiency in the supply of water has been the normal condition under which crops have had to be raised previous to the introduction of irrigation. Cotton cultivation, for instance, appears to suffer from a too liberal supply of water. It was said some years ago, with reference to the cotton crop in Egypt, that the shorter the water supply the greater the yield of the crop. This generalisation, based on the figures of a few years only, could obviously be discredited by a *reductio ad absurdum*. But the figures of the cotton crop of Egypt for late years seem to show that over-watering is practised when the opportunity offers, and that over-watering is followed by a decrease in yield. The total yield for all Egypt in 1897 was 6,513,444 cwt.; in 1899, 6,432,776; in 1901, 6,369,911. For the intermediate years it was less. In 1903 the Assuan reservoir was filled and drawn upon for the first time, and there was a considerable extension of the area put under cotton in 1903 and 1904. Nevertheless, in both those years the yield was less than it had been in 1901. There was no advance on the record figure of 1897 in spite of the extension of the area under crop. The official reports of the Irrigation Department of Egypt state that the water supply of 1903 and 1904 "was everywhere plentiful; too plentiful perhaps." It is possible that, as the area increases under the

stimulus of the increased supply and the water allowance per acre becomes less, the yield per acre may again rise to as high a figure as it had reached before the Assuan dam came into operation. If so, the record total yield of Egypt of 1897 will then be surpassed by a considerable figure. Now, in the Irrigation Report for 1904, it is stated that the "duty" that was got out of the water in the summer of 1904 was "probably the lowest ever recorded," and that there had not been such a good summer supply in the river since 1899. The moral of this would seem to be that, if a given quantity of water is best suited to any crop, it is a mistake to give more than that quantity; and the irrigation officers would be acting in the interests of the farmers if they were to make excessive watering impossible by withholding the super-abundant supply, even if so doing necessitated running water to waste. But to run water to waste when cultivators are demanding more, even though giving way to the demand would be prejudicial to their interests, is an unpopular thing to do, and is a difficult policy to carry out in the face of an almost universal belief that, in a conflict of opinions between the irrigation officer and the agriculturist over a question concerning crop requirements, the former must necessarily be in the wrong. A good irrigation engineer will be all the better for a sound knowledge of the agricultural conditions and needs of the district which is or will be affected by the canal system under his control, and it is part of his duty to acquire such knowledge, so as to enable him to apply his professional ability to the best advantage.

The limitation of the water supply, in a healthy system of canals, to the real requirements of the crops, has a further advantage beyond the prevention of over-watering. It also protects the drains, which have to carry off the excess, from being over-worked to such an extent that they cannot perform their part efficiently. When the excess that reaches them is reasonable in quantity and no more than they have been designed to carry off, the evils of water-logging and stagnation are avoided.

It has been said that irrigation water, to be entirely beneficial, must reach everywhere, but remain nowhere. The putting into practice of this theoretical formula is most difficult in the case of the low-lying lands of flat slope which lie along the sea-ward margin of most deltas. Such lands are often salted, and the problem of their reclamation is, therefore, not solved by merely getting rid of the water that covers them permanently or occasionally, and by draining them; but the salt that makes the land infertile must be washed out of it. The land surface is so little above sea-level that drainage by gravitation, or free flow, is an impossibility. The water has to be got rid of by pumping. There are wide stretches of low-lying level lands, at present barren wastes and marshes, lying unreclaimed along the north margin of the delta of Egypt. There is so much else in Egypt that it pays better to reclaim or develop, that it will be many years yet before cultivation extends northwards from its present limit as far as the borders of the sea.

The reclamation of such lands, however, is a possibility. Holland, and the valley of the Po in Italy, furnish instances of successful reclamation. The first thing to do is to get rid of the salt in the soil. If the flood water of the river can be made to flow freely over the surface, some of the salt will be carried away in the water. But it is not often possible to secure surface washings sufficiently copious or prolonged to remove the salt for more than a comparatively shallow depth. The salt below is more effectually got rid of by a system of deep drains into which the water finds its way by downward percolation through the soil, carrying the salt with it. These operations of surface washings and subsoil drainage can be effected in the following way. The land to be reclaimed would be surrounded by a bank to exclude all water other than that purposely admitted. The earth to form the bank would be obtained from a ditch dug along the inside of it to a regular section to serve as a collecting drain. At the higher end of this enclosure, at the most convenient point, a head sluice on the feeder canal would admit

water under control. At either end of the lower side escapes would provide exits for the water of surface washings. At the lowest point of the enclosure, or at the most convenient point on the interior drain, a pump to lift the drainage water would be set up. Irrigating channels in connection with the head sluice would distribute the water admitted over the enclosed area, and drains, alternating with the irrigating channels, would lead to the pumping station. The first operation of surface washing would then be conducted, during the season when water was plentiful, by opening the head-sluice and keeping the escapes closed until the whole of the enclosed area was covered with a sheet of water. As soon as that had occurred, the escapes would be opened to the extent necessary to discharge as much as was being admitted through the head sluice, so that the water level in the enclosure might remain constant. When it was no longer possible to continue the supply, the head sluice would be closed, the escapes be fully opened, and the water run off to as low a level as it would go. When it ceased to flow, the escapes would be closed to prevent a back flow, and the pumps would lift the remaining water into a discharging channel outside the enclosure, which would carry it away. The drain along the inside of the enclosing bank and the drains all over the area, alternating with irrigating channels, would lead all excess water to the pumping station and keep the saturation level low. The head-sluice would admit the supply required for the irrigation of the crops or for other operations, and the irrigation channels would distribute it. The surface washing would probably have to be repeated more than once before the soil would become cultivable.

But meanwhile, after a surface washing, supposing water is available, the system of subsoil drainage would be brought into play to do its part in getting rid of the salt. The method of proceeding consists in surrounding plots of land of convenient dimensions by ridges, and filling the enclosed plots with water of, say, one foot in depth. The water in the deep drains alongside the plots is kept low by the pumps. The water

covering the plots sinks into the ground and percolates downwards and outwards to the drains, carrying salt with it. The plots are filled again and again, and the process repeated till the soil is sufficiently free of salt to be cultivable.

Finally, to enrich the soil, the turbid flood water should be admitted and kept standing in the enclosed area long enough to throw down its fertilising matter, and be then run off. It is well to make provision, in the arrangements for the reclamation of these low lands, for periodical washings every third year or so, as their tendency is to return to their original salted condition ; and it is therefore necessary to adopt effective measures to counteract the tendency.

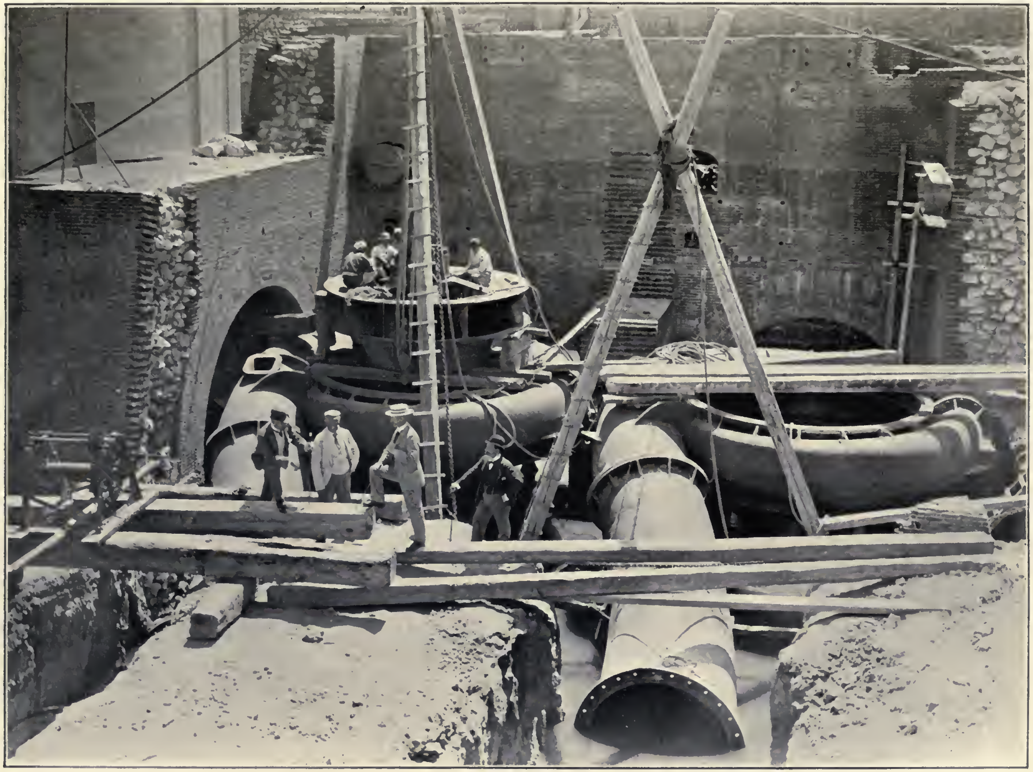
Whether it is worth while to incur the expenditure of reclaiming land which, it might be urged, Nature has not intended for cultivation, depends upon many things. It has been argued that, inasmuch as it pays to lift water for raising crops by irrigation on high lands which get free flow drainage, it should pay to bring land under cultivation by lifting the drainage water that runs off land which enjoys free flow irrigation, because the amount drained off irrigated land must of necessity be less than the amount supplied for its irrigation. This argument would be conclusive if the yield of the crops in both cases were the same. But that is often by no means the case, the low lands after reclamation being generally poor in quality in comparison with the high lands. In Egypt the high lands near the head of the delta, for the irrigation of which water has to be pumped, yield twice as much cotton per acre as the low lands in the north of the delta near the sea.

There is another difficulty which must not be lost sight of in considering the *pros* and *cons*. of any reclamation scheme. There would generally be a want of hands to carry out the operations of reclamation and farming, as no villages or habitations would be found on waste lands that produce nothing. The population would have to be brought from elsewhere and given inducements to settle. Means of transport would also have to be provided

for the conveyance of the produce of the land to a market where it could be sold. In Chapter I. it has already been told how, in India, a new population of 1,000,000 has founded homesteads on some 2,000,000 acres of waste land which have been reclaimed to cultivation by the waters of the Chenab Canal. But it is not all countries that have such human reserves as India has to draw upon; and want of population will often necessitate the postponement of reclamation schemes.

Another important consideration in estimating the financial prospects of any scheme involving pumping on any considerable scale is the cost of the fuel required for generating power by steam, electricity or other means, whether the object is irrigation or drainage. For fuel is the most important item in the pumping expenditure. Large pumping stations work more economically than small ones, the establishment and other charges being relatively less in a large than in a small installation. There is a large pumping station at Mex (Plate IX.), near Alexandria, which works in the interests of drainage. A large area of the western delta of Egypt drains into Lake Mareotis, and the efficiency of the drains depends on the control of the surface level of the lake. It is the business of the Mex pumps, therefore, to keep the lake surface from rising above a certain fixed level. The pumping station consists of two 48 inch centrifugals with horizontal shafts, and 5 centrifugals with vertical shafts (shown under erection in Plate IX.) worked by four engines of an aggregate of 520 I.H.P. It is capable of lifting a maximum of 35 cubic metres (1,227 cubic feet) per second. The pumps work for about five months in every year more or less continuously, and lift from 300,000,000 to 400,000,000 cubic metres during that period. The quantity of coal expended per 1,000,000 cubic metres lifted varies from 18 to 20 tons, the lift being from 2½ to 3 metres. The cost per 1,000,000 cubic metres lifted varies from £32 when the price of coal delivered at the pumps is 25*s.* a ton, to £45 when the price of coal is 36*s.* a ton, as it was in 1900.[1]

[1] In 1905 the cost per 1,000,000 cubic metres lifted fell to £29.



MEX PUMPS UNDER ERECTION.

A much smaller pumping station at Kassassin, also for drainage purposes, lifts water $2\frac{1}{2}$ to 3 metres at a cost of £40 to £45 per 1,000,000 cubic metres, when coal delivered at the station costs 28*s*. the ton. This station is capable of lifting $2\frac{1}{2}$ cubic metres (88 cubic feet) a second. It is composed of two 30 inch and one 20 inch centrifugal pumps. With smaller stations the cost per unit of volume pumped would be considerably higher. Sir William Willcocks, nevertheless, recommends small pumping stations in the case of reclamation work. In his lecture on Irrigation on the Tigris, delivered in Cairo on March 25th, 1903, he expresses his opinion in the following words:—"The important point is, that numbers of small pumps should be placed on the banks of the main drains, draining small areas and discharging direct into the mains. Such pumps should be actuated by one central electric station for reasons of economy. The results of such drainage would be immediately apparent. The early failures of large reclamation works were nearly always due to the extensive areas drained by single installations." He considers the most economical area to drain with one pump to be 2,500 acres.

The new departure of the Irrigation Service of India in adopting a pumping scheme for the irrigation of the Divi Island, on the Kistna river in Madras, has already been referred to at the end of Chapter VI. As was there stated, the pumping station will consist of eight 160 brake-horse-power Diesel oil engines, each actuating a Gwynne centrifugal pump with a 39 inch diameter discharge pipe. The pumps are intended to lift water 10 to 12 feet for the irrigation of 50,000 acres. The estimated cost of the first installation is, in round figures, £35,000. The quantity of water to be lifted will be 500 cubic feet a second. The fuel to be used is oil. The estimated annual expenditure, with a pumping season of 4 months continuous work lifting 500 cubic feet a second, is £7,384 for a total quantity lifted of 5,184,000,000 cubic feet. This gives a rate of £1 8*s*. 6*d*. per 1,000,000 cubic feet, or £50 per 1,000,000 cubic metres, lifted.

CHAPTER XIII.

NAVIGATION.

THE waterway provided by the construction of an irrigation canal is often adapted to navigation. Whether it is desirable to make one and the same canal serve two masters is a question that has been much disputed by the canal engineers of India, ever since Sir Arthur Cotton, in 1854, preached the gospel of navigation. The question does not seem to be finally settled yet. It is probable that the combination of irrigation and navigation is desirable in some cases and not in others, but that it is not so generally desirable as the early enthusiasts for navigation asserted. In a paper on the Navigable Waterways of India, read on Feb. 15th, 1906, before the Indian Section of the Society of Arts by Mr. R. B. Buckley, C.S.I., it was shown that, out of a total length of 11,858 miles of irrigation canals, in India, 2,778 miles were navigable. Judged by the receipts credited under the head of navigation, it cannot be said that, as a rule, there has been a satisfactory return for the expenditure incurred in adapting irrigation canals to navigation. Mr. Buckley mentions the Godavery system in Madras, and the Orissa and Midnapore systems in Bengal, as the canals in which navigation has been most successfully combined with irrigation.

An irrigation canal should follow the line which is best suited to it as an irrigating channel; a navigation canal should connect the producing areas with the markets, where the products are to be disposed of, by the most direct line that may be economically possible. It is not likely that the two lines would be identical, though occasionally they might be. If

irrigation and navigation are to be partners in one business, there must be compromises arranged, since what is best for the one is not so for the other. The principles on which an irrigation canal should be designed have been pointed out in Chapter VIII. It was shown that the velocity of flow should be such that there would be neither deposit of silt nor scour of the bed or banks. A velocity complying with these conditions might very easily be too high for the convenience of navigation, which would be better suited by a sluggish current or no current at all. It has also been explained in Chapter X. that it is desirable for economical distribution of water in irrigation to regulate the discharges in the canals so that periods of low supply should alternate with periods of high supply. Such a fluctuating system would be very disconcerting to boats, at any rate when fully laden. There are besides other respects in which irrigation and navigation requirements conflict when the same canal has to satisfy both. Nevertheless it is sometimes advantageous, all things considered, to make an irrigation canal navigable, so that it may not only furnish the means for raising products of the soil, but may also offer facilities for transporting the same products to market. The importance of inland waterways as affording a cheap method of transport for bulky goods of all descriptions has received practical recognition in France, Belgium, Germany and America to the great advantage of their trade. But the canals which form part of their schemes of inland waterways are, for the most part, designed exclusively for navigation purposes, and are unconnected with irrigation. It is in India and Egypt that examples of canals serving both objects will be found.

A navigable canal, or navigable system of canals, must, in the first place, have uniformity of gauge, that is, the locks should all have the same dimensions and the canals an uniform cross section, so that the largest sized craft that can navigate any part of the system can navigate it throughout.

When an irrigation canal has to be adapted to navigation, it

is necessary to reduce the velocity of flow so that it may not exceed from $1\frac{1}{2}$ to 2 feet a second. As in most cases, when this condition is complied with, the water-surface slope of the canal will be less than that of the land surface, it will be necessary to provide falls at intervals along the canal, so that when the water level has reached the maximum height above country level that is convenient, it may be dropped down within soil. At each point where a fall is necessary, a lock must be built to give passage to boats between the upper and lower reaches.

There are three different positions in which the lock may be placed with reference to the fall with which it is associated. The fall may be placed on the main canal, and the lock on a side channel taking off from the canal above the fall and rejoining it below. Or the lock may be on a navigable channel dug on the direct line of the canal axis, while the fall is placed on the main channel which is diverted round the lock on a curved alignment. In both these cases the fall and lock are usually built in such positions that the roadway over the two may be in one straight line. The third plan is to make a combined work of lock and fall, and to have no side channel. The advantage of the last arrangement is that the entrance to the lock is kept clear of silt; the disadvantage is, that when the discharge over the fall is considerable, the draw of the current may make it difficult, or even dangerous, for boats to enter the lock. On the other hand, the disadvantage of placing the lock on a separate channel from the fall is that the channel above and below the lock has a tendency to silt up, and, if not kept clear by dredging or otherwise, boats may find it not merely difficult, but impossible to enter the lock. But a lock so placed has the advantage that the entrance and exit of boats is effected in still water.

Sometimes, instead of a fall or weir to hold up the water with the object of reducing the velocity of flow or of producing a sufficient depth for boats in the reach above, a regulator is

necessary for the purpose of raising or lowering the water level to suit the needs of irrigation. Whenever the regulator may be used to hold the water in the upper reach at a higher level than that in the lower reach, the lock comes into action for the passage of boats; but when the regulator is fully open, both pairs of lock gates also can be opened, and boats be passed freely without the necessity of bringing the locking arrangements into operation.

The chamber of a lock may be looked upon as a very short reach of canal with regulators at the upper and lower ends, by means of which the water level between them can be raised and lowered at will to the levels of the reaches above and below respectively, so that boats may be raised or lowered from one to the other. The pairs of lock gates with their face sluices, and the filling and emptying side sluices, perform the office of regulators. In fact, it sometimes happens that a reach of a canal is treated as a lock. If the discharge of an irrigation canal, which is navigable, falls below the normal minimum contemplated when grading the canal, or if the bed is raised by silt deposit, boats often run aground at the upper end of a reach, or in the down-stream exit channel of the lock, and are either unable to enter the lock if ascending the canal, or to leave the lock if descending. It then becomes necessary to hold up the water by regulation at the lower end of the reach, so that there may be depth of water enough for boats to pass in and out of the lock at the upper end of the reach. A very large lock might be economically made on a canal by separating the two pairs of gates and their sluices into two distinct works with the chamber between them formed by a convenient length of the earthen channel of the canal. In harbours the lock chamber is sometimes developed into a basin of considerable area. But the dimensions of canal lock chambers are limited for reasons other than economy of construction. Economy of water in the working of a canal is often a more important consideration than economy in the first cost of construction.

Every time boats are passed through a lock, a volume of water equal to that required to raise the level in the lock chamber from that of the lower to the higher reach has to be passed forward from above to below the lock. In irrigation canals—in their upper reaches at any rate—this is not a serious matter, as the passing forward of water is always required to feed the distributing canals. But in purely navigation canals, where the supply of water for keeping the reaches full is extremely limited, economy of the available water supply may become a question of first importance, calling for devices such as lifts and inclines to promote economy. Another matter affecting the dimensions of lock chambers is the value of time. Given the same discharging capacity of sluices, a large lock naturally takes longer to fill than a small one, and the time taken by the canal traffic to pass from one reach to the other would be greater with the large lock; and unnecessarily greater, whenever the lock space is only *partially* utilised by passing boats or barges. The dimensions of the lock should therefore be determined by the traffic which may be expected to use the canal, and should not be excessive.

The most common form of lock gates is that in which a pair of gates meet at an angle and are pressed against each other and against a bed sill by the head of water bearing against them. The gates may be of wood or iron, and the sill faces of wood, iron or masonry; but wood is not used in important locks. A less common form is the single leaf gate, which spans the lock chamber from side to side and bears against vertical faces in the sides of the lock. To open the lock, the gate is withdrawn sideways into a recess built at right angles to the lock chamber. In the locks of the Assuan dam such a single leaf gate has been the form adopted. It is hung from above by seven pairs of sling rods, attached to two sets of free rollers, which are free to move along two bascule girders spanning the lock. The gate is withdrawn into a recess in the side of the lock by the movement of its supporting rollers along the bascule

girder. When the gate is safely housed in its recess beyond the pivoting end of the bascule girder, the latter is raised into a vertical position to free the passage way for vessels using the lock. The opening and closing of the valves of the lock gates, the moving of the gate backwards and forwards, and the lifting of the bascule girder, are all effected by hydraulic power. The system adopted at Assuan has proved expensive, and is not likely to be imitated for gates of smaller dimensions than those of the Assuan dam locks.

In some cases the single leaf gate, instead of being suspended from above, rests upon the floor of the lock; and, to facilitate its movement backwards and forwards from and to the recess, arrangements are made for floating it.

A lock has, in certain situations, to be furnished with gates to act when the normal head is reversed. Such conditions would exist where a lock constituted the connecting work between the terminal reach of a canal and a tidal harbour. In such a case the gates would have to be duplicated, so that the levels in the lock might be controlled on whichever side the higher water might be.

As time is often a serious consideration in the transport of goods, and as every lock on a navigable line is a source of delay, it is important to arrange for passing boats through locks as quickly as possible. To this end means must be provided for rapidly filling and emptying the lock chamber. The Manual on Irrigation Works of the College of Engineering in Madras lays it down that "locks should be capable of being filled or emptied in three minutes." The filling and emptying is effected by sluices in the lock gates, often assisted by sluice ways built round the gates in the thickness of the lock walls. The discharging capacity of the sluices must be sufficient to effect the filling or emptying of the lock within the maximum period permissible. The filling sluice-way in the lock walls is sometimes carried along the whole length of the chamber, and is given several outlets into it at intervals along its length with

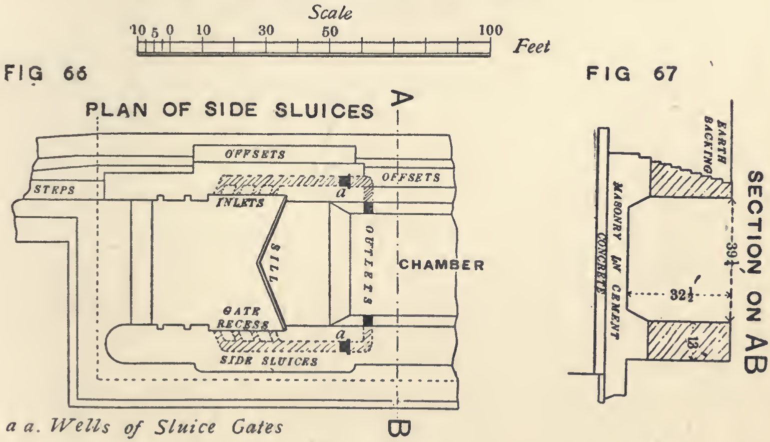
the object of diminishing the back-waters and eddies which are produced, to the inconvenience and sometimes danger of boats, when the inflow is concentrated at one or two points only.

But the most important matter affecting the disposition of the sluices is the tendency of silt to deposit against the up-stream face of the gates, creating thereby an impediment to their opening. To counteract this tendency, sluices are fitted in the face of the lock gates at as low a level as the design of the gates permits. The inlets of the side sluices in the masonry of the lock walls are also so disposed as to create a scouring action over the floor immediately up stream of the gates. In the case of a lock fitted with the ordinary pair of gates meeting at an angle, the inlet openings to the sluice way are made in the face of the recess in which the gate lies when fully open; and their sills are placed on a level with the floor over which the gates move. In the *Z*ifta barrage lock there are three such inlets in each gate recess communicating with one united sluiceway, which in the case of the upper gate sluices (Fig. 66) leads to an outlet into the lock chamber, and in the case of the lower gate sluices into the channel below the lock. Difficulties arising from silt deposit above and within locks are especially met with in the case of locks at the off-take of a canal from a muddy river, and on irrigation canals adapted to navigation, which carry silt laden water for the sake of the cultivation served by them. An intelligent and experienced lock-keeper in charge of a lock with well designed sluices can do much, by a skilful manipulation of the sluice gates, to minimise the inconveniences arising from silt deposit.

The chamber walls of a lock when empty act as retaining walls to support the earth backing. The dimensions, however, of an ordinary retaining wall are considered insufficient for a lock wall, as the rapid emptying of the lock chamber brings pressures to bear on the wall which are somewhat in the nature of those due to a live load. If the wall has an interior vertical

face, a thickness of 3 feet at the top, and a back batter of 1 in 4 obtained by offsets, will give a profile that is suitable in most cases. The Zifta barrage lock (Fig. 67) furnishes an example of a lock with interior vertical faces; the Assuan lock (Fig. 68) that of a lock having interior faces built with a batter. Though the latter gives a better disposition of the material for resisting the pressure of the backing, there is, in some cases, a serious objection to diminishing the width of the lock chamber between high water and low water levels. For if, when the water in a

ZIFTA BARRAGE LOCK



a a. Wells of Sluice Gates

lock with interior face batter is at the level of the upper reach, boats are admitted in such numbers that they completely fill the lock from side to side, they will do more than fill it when the water is lowered, and may be capsized by one side being held up against the lock wall while the other sinks with the water.

As a rule, from 15 to 16 feet is about the maximum difference of level that is overcome by one lock. If the difference is greater, the change of level is effected by two locks, a double lock, or a flight or ladder of locks. The total drop at the Assuan dam, from the high water level in the reservoir above the dam to the river low water level below it, is 66 feet. To

pass boats, a four-fold flight of locks has been provided on one flank of the dam.

It is a not uncommon thing for a longitudinal crack to appear in the floor of a lock under construction, when the walls have reached a certain height. This occurs when the soil on which the lock is built is compressible, and the pressure over

UPSTREAM LOCK ASSUAN DAM

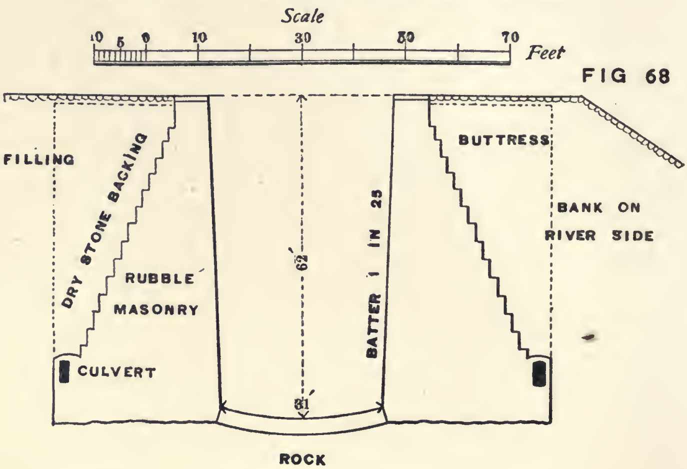


FIG 68

the area of the foundations is unequally distributed, producing uneven settlement. If the centre of pressure of the weight of the wall and its earth backing falls so far behind the centre of the figure of the base as to be beyond the safe limit, the inequality that produces settlement is established. But this result can be avoided by giving the base a considerable width and lightening the back of the walls by a distribution of void spaces in the thickness of the masonry.

APPENDIX I.

WEIGHTS AND MEASURES.

Weights.

1 cubic foot of water weighs 62½ lbs.
1 cubic metre of water weighs 1 ton (very nearly).
1 kilogramme = 2·2046 lbs.
1 lb. = ·4536 kilogramme.
1 lb. per square inch = ·0703 kilogramme per square centimetre.
1 kilogramme per square centimetre = 14·22 lbs. per square inch.

Lineal Measures.

1 metre = 3·2809 feet.
1 foot =·3048 metre.
5 miles = 8 kilometres (approx.).

Square Measures.

1 square metre = 10·7643 square feet.
1 square foot = ·0929 square metre.
1 acre = 4046·71 square metres.
1 feddan = 4200·83 square metres.
1 feddan = 1·038 acres.
1 hectare = 10,000 square metres.
1 hectare = 2·4711 acres.
1 square mile = 640 acres.
1 square mile = 27,878,400 square feet.
1 square kilometre = 100 hectares.
1 square kilometre = 247 acres.

Cubic Measures.

1 cubic foot = 6·2355 gallons.
1 cubic foot = 28·3 litres.
1 cubic foot = ·028315 cubic metre.
1 cubic metre = 35·3166 cubic feet.
1 cubic metre = 61,028 cubic inches.
1 litre = 61·02 cubic inches.
1 litre = ·0353 cubic feet.

1 litre = ·22 gallon.
1 litre = ·88 quart.
1 litre = 1·76 pint.
1 cubic metre = 220·097 gallons.
1 gallon = ·004543 cubic metre.
1 acre foot = 43,560 cubic feet.
1 acre foot = 1233·4 cubic metres.
1,000,000 cubic feet = 23 acre feet (approx.).

Discharge Measures.

1 cubic foot a second is sometimes abbreviated to
1 cusec in India, and to
1 second foot in America.
1 second foot = 50 California, Nevada, Idaho, or Utah inches.
1 second foot = 38·4 Colorado inches.
1 cubic foot a second amounts to 86,400 cubic feet a day, or 2,445 cubic metres a day.
1,000,000 cubic metres a day is given by a discharge of 11·5741 cubic metres a second, or 409 cubic feet a second.
1 cubic foot a second for 30 days gives 59½ acre feet.
1 cubic foot a second for 24 hours gives 2 acre feet (approx.).
100 California inches for 24 hours gives 4 acre feet.
100 Colorado inches for 24 hours gives 5⅛ acre feet.
1 acre foot is given by 25·2 California inches in 24 hours.

Duty of Water.

Equivalent Expressions.

1 cubic foot a second per 100 acres gives the same allowance as
1 cubic metre a second per 1430 hectares, or 1 cubic metre a second per 3402 feddans, or 25·4 cubic metres a day for each feddan.
1 litre per second per hectare gives the same allowance of water as 1 cubic foot per second per 70 acres.

APPENDIX II.

FORMULAS AND DISCHARGE MEASUREMENTS.

THE formulas in most common use by irrigation engineers are those which relate to the flow of water in open channels; to discharges over weirs, both clear overfall and submerged; and to discharges through the vents of canal or river regulators, lock sluices and syphon barrels.

The fundamental formulas on which the whole science of hydraulics is based are three, namely :—

Formula (1). $Q = A \times V.$

Formula (2). $V = c\sqrt{2gH}.$

Formula (3). $V = c\sqrt{RS}.$

The symbols contained in these formulas have the following significations :—

A is the area of any section of discharging waterway.

V is the mean velocity of that section.

Q is the discharge.

g is gravity acceleration.

H is the head of water.

c is a co-efficient (given in Tables) depending on the nature and condition of the discharging waterway.

R is the hydraulic mean depth or mean radius; its value is obtained by dividing the area of the water cross section by its wetted perimeter.

S is the hydraulic slope or sine of the inclination of the water surface, or, in other words, the fall of water surface per unit of length of channel.

Formula (1) is applicable in all cases; Formula (3) is applicable to open channels; Formula (2) to sluice ways.

The formulas for weir discharges are deduced from Formula (2). That for a clear overfall weir, without velocity of approach, is

Formula (4). $Q = \frac{2}{3} c \times A\sqrt{2gh}$

in which h is the depth of water on the weir sill. In this case A = the length of the weir crest $\times\ l$.

The formula for a submerged weir, without velocity of approach, is

Formula (5). $Q = c \times l \sqrt{2 \cdot gd_1} \{d_2 + \frac{2}{3} d_1\}$.

in which l is the length of the weir crest,

d_1 is the difference of level between the water surfaces up stream and down stream of the weir,

and d_2 is the depth of the sill crest below the down-stream water surface.

If there is velocity of approach, as is usually the case with canal falls, allowance has to be made for it. The head of water which would produce the known velocity of approach must be calculated from Formula (2)—$V = c \sqrt{2\ gH}$—and be added to the head of water in Formulas (4) and (5). In Formula (4) it is added to h, in Formula (5) to d_1.

The value of gravity acceleration g varies in different parts of the world, from 32·25 to 32·09 feet per second: but it is usually taken as 32·2 feet per second; and that is the figure to substitute for g in the formulas when English measures are used. But if metric measures are used, $g = 9{\cdot}83$, the equivalent for 32·2 feet a second. Confusion will result, when using the formulas containing g, if a change is made from one system of measures to another and this alteration of the numerical value of g is forgotten.

The value of the co-efficient c is given in Tables for different values of R, the hydraulic mean depth. But here again, the value of c changes with change of measures employed, and separate Tables of Values for c are required for R in feet and R in metres. Bazin's Values have, perhaps, been more generally accepted than others by hydraulic engineers, and are, therefore, here given—Table I. for use with English measures, and Table II. for use with metric measures :—

TABLE I.

BAZIN'S VALUES OF c IN THE FORMULA $V = c \sqrt{RS}$ FOR USE WITH ENGLISH MEASURES.

Hydraulic Mean Depth. R in Feet.	Material of Bed and Sides of Channel.			
	Plastered. Planed Planks.	Dressed Stone. Brickwork.	Rubble Masonry.	Earth.
·25	125·4	94·8	56·5	25·9
·50	135·3	108·8	72·0	35·7
·75	139·1	115·0	80·8	42·6
1·00	141·2	118·5	86·7	47·9
1·25	142·4	120·8	90·9	52·3
1·50	143·3	122·4	94·0	56·0
1·75	143·9	123·6	96·5	59·2
2·00	144·4	124·5	98·5	62·0
2·50	145·1	125·8	101·5	66·6
3·00	145·6	126·7	103·6	70·4
3·50	145·9	127·3	105·2	73·5
4·00	146·1	127·8	106·5	76·1
5·00	146·5	128·5	108·2	80·2
6·00	147	129	110	83·4

TABLE I.—*continued.*

Hydraulic Mean Depth. R in Feet.	Material of Bed and Sides of Channel.			
	Plastered. Planed Planks.	Dressed Stone. Brickwork.	Rubble Masonry.	Earth.
7·00	147	129	110	86·0
8·00	147	130	111	88·0
10·00	147	130	112	91·2
12·00	147	130	113	93·4
15·00	147	130	114	95·9
20·00	148	131	115	98·6
40·00	148	131	116	103·1
70·00	148	131	116	105·2
100·00	148	131	116	106·1
Inf.	148	131	117	108·3

TABLE II.

BAZIN'S VALUES OF c IN THE FORMULA $V = c\sqrt{RS}$ FOR USE WITH METRIC MEASURES.

Hydraulic Mean Depth. R in Metres.	Material of Bed and Sides of Channel.			
	Plastered. Planed Planks.	Dressed Stone. Brickwork.	Rubble Masonry.	Earth.
0·05	65	47	26	—
0·10	72	56	35	16
0·15	73	60	40	20
0·20	76	62	43	22
0·25	77	64	46	24
0·30	78	65	48	26
0·35	78	66	49	28
0·40	79	67	51	29
0·50	79	68	53	32
0·60	80	69	54	34
0·70	80	69	55	36
0·80	80	70	56	37
1·00	80	70	58	40
1·50	81	71	60	44
2·00	81	71	61	47
2·50	81	72	61	49
3·00	81	72	62	50
4·00	81	72	63	52
5·00	81	72	63	54
10·00	81	72	64	56
15·00	81	72	64	57

The above Tables of values for c takes into account the roughness of the bed and the hydraulic mean depth, but not the hydraulic slope, which in extreme cases has to be considered. In all ordinary canals and rivers the

value of c is not affected by the slope. But in mountain torrents and in channels with a very gentle surface slope, such as the tail reaches of rivers near the sea, the hydraulic slope is a factor to be taken into account for determining the correct value of c. The formula, known as Ganguillet and Kutter's, embraces this consideration, the value of c in the formula, $V = c\sqrt{RS}$, being represented by the expression

$$\frac{a + \frac{l}{n} + \frac{m}{S}}{1 + \left(a + \frac{m}{S}\right)\frac{n}{\sqrt{R}}}$$

in which n is the coefficient of roughness depending on the nature of the surface of the channel, and a, l and m are constants derived from experiment, the other letters having the same signification as in Formula (3) above.

When the values of the symbols in the formula are expressed in English feet, a, l, and m have the following values:—

$a = 41{\cdot}6604676.$
$l = 1{\cdot}8113250.$
$m = 0{\cdot}0028075.$

When metrical measures are used,

$a = 23.$
$l = 1.$
$m = {\cdot}00155.$

n has the following values for channels of different surfaces:—

Values of n.	Nature and Material of Channel.
$n = {\cdot}010$	Plaster in pure cement: planed timber: glazed, coated or enamelled stoneware and iron pipes: glazed surfaces of every sort in perfect order.
$n = {\cdot}013$	Ashlar and well-laid brickwork.
$n = {\cdot}017$	Brickwork, ashlar and stoneware in an inferior condition: rubble in cement or plaster, in good order.
$n = {\cdot}025$	Canals and rivers in earth of tolerably uniform cross-section, inclination and direction, in moderately good order and regimen, and free from stones and weeds.
$n = {\cdot}035$	Rivers and canals with earthen beds in bad order and regimen, and having stones and weeds in great quantities.

Experience is required for the assignment of the correct value to n. Its usual value for the earthen channels of an ordinary canal system in normal condition would be ·025.

The calculation of discharges from hydraulic formulas is much facilitated by the use of Tables made for that purpose. In India, where discharges are measured in feet, Higham's "Hydraulic Tables" and Jackson's "Canal and Culvert Tables" are most in favour. "New Tables for the complete

solution of Ganguillet and Kutter's Formula for the flow of liquid in Open Channels, Pipes, Sewers and Conduits," by Colonel E. C. S. Moore, R.E., M.S.I., will also be found useful by calculators who work with English measures. In Egypt, where the metrical system is current, "Elementary Hydraulics," by Willcocks and Holt, is a safe and simple guide to the practical use of hydraulic formulas. "The Civil Engineer's Pocket Book," by Trautwine, shows how the formulas should be used in both cases, that is, with English and metric measures. But it is, perhaps, advisable, in dealing with formulas which, to many, may be sufficiently intricate without unnecessary complication, to make use of a book of reference on the subject which deals exclusively either with formulas and coefficient values adapted to English measures, or with those adapted to metric measures; and not to one which, like this Appendix, attempts to deal with both. However, as this book may, on occasion, possibly be available when others are not, the two following Tables are given, from which the values of c in Kutter's formula may be obtained for the usual value of n—viz., ·025—applicable to the ordinary channels of a canal system.

TABLE III.

(For use with English Measures.)

KUTTER'S VALUES OF c IN THE FORMULA $V = c\sqrt{RS}$ FOR ORDINARY CHANNELS IN NORMAL CONDITION, WHEN $n = \cdot025$.

Hydraulic Mean Depth R in feet.	S $\frac{1}{40,000}$	S $\frac{1}{20,000}$	S $\frac{1}{10,000}$	S $\frac{1}{5,000}$	S $\frac{1}{2,500}$	S $\frac{1}{1,000}$	S $\frac{1}{100}$
·10	17	20	22	24	25	27	27
·20	24	26	29	31	32	34	34
·40	32	35	38	40	42	43	44
·60	38	41	44	46	47	48	49
·80	43	46	48	50	51	52	53
1·00	47	49	52	54	55	56	56
1·50	55	57	59	60	61	62	62
2·00	61	62	64	64	65	66	66
3·00	70	71	71	71	71	71	71
3·28	72	72	72	72	72	72	72
4·00	78	77	76	76	76	75	76
6·00	88	85	84	82	81	81	81
8·00	96	91	88	87	85	84	83
10·00	102	96	92	89	88	87	86
12·00	107	99	94	92	90	88	87
16·00	115	106	99	94	93	91	90
20·00	121	110	102	98	96	94	93
30·00	133	118	108	103	99	96	95
50·00	147	127	114	108	104	101	100
75·00	157	133	118	111	106	103	102
100·00	163	137	121	113	108	105	104

TABLE IV.

(For use with Metric Measures.)

KUTTER'S VALUES OF c IN THE FORMULA $V = c\sqrt{RS}$ FOR ORDINARY CHANNELS IN NORMAL CONDITION, WHEN $n = \cdot025$.

Hydraulic Mean Depth R in metres.	S $\frac{1}{40,000}$	S $\frac{1}{20,000}$	S $\frac{1}{10,000}$	S $\frac{1}{5,000}$	S $\frac{1}{2,500}$	S $\frac{1}{1,000}$	S $\frac{1}{100}$
·025	9	10	11	12	13	13	14
·05	12	13	15	16	17	18	18
·10	17	18	19	20	21	22	22
·20	22	23	24	25	26	27	27
·30	26	28	29	30	30	31	31
·50	31	32	33	34	34	35	35
1·00	40	40	40	40	40	40	40
2·00	50	48	47	46	45	45	45
3·00	56	53	51	49	48	48	47
5·00	64	59	54	53	52	51	50
10·00	75	66	60	57	55	54	53
15·00	81	71	63	59	57	56	55
20·00	85	72	64	60	58	57	56
30·00	90	76	67	62	60	58	57

The formulas (2), (4) and (5), for calculating the discharges of sluices, weirs and syphons, apply to any system of measures, to the metric as well as to the English. But it is necessary that the head, the length or area, and the acceleration of gravity (g) should all be in the same unit—either all in feet, or all in metres, or all in any other unit of measurement. The discharges will also be in the cube of that unit. The value of g, as has been stated already, is 32·2 feet in English measure, and 9·83 metres in metric. The values of c given in the following table are the same whatever system of measures may be used; since c in each of the formulas (2), (4) and (5) $= \frac{\text{actual discharge}}{\text{theoretical discharge}}$, a relation which is independent of systems of measures.

TABLE V.

VALUES OF c GENERALLY EMPLOYED IN PRACTICE WITH DISCHARGE FORMULAS OF SLUICES, WEIRS AND SYPHONS. FORMULAS (2), (4) AND (5).

Description of Discharge Waterway.	Coefficient c.
Ordinary lock sluices and small sluices	·62
Clear overfall weirs	·62
Small regulator openings with shallow water	·57

TABLE V.—*continued.*

Description of Discharge Waterway.	Coefficient c.
Regulator openings, under 6 feet or 2 metres in width, with recesses in the piers	·62
Ditto, ditto, with straight continuous piers	·72
Regulator openings between 6 and 13 feet (2 and 4 metres) in width, with recesses in the piers	·72
Ditto, ditto, with straight continuous piers	·82
Regulator openings over 13 feet (4 metres) in width, with recesses in the piers	·82
Ditto, ditto, with straight continuous piers	·92
Short straight pipes as in syphons	·82
Short bent pipes as in syphons	·72

Formula (3), $V = c \sqrt{R S}$, for open channels is of more practical use in the preparation of a project—to determine, for example, the dimensions of a canal or the possible maximum discharge of an existing natural waterway—than it is to ascertain the actual discharges of flowing canals. The more usual way of gauging actual discharges is to ascertain the mean velocity by direct observations made with floats. The mean velocity itself may be observed by special floats in the form of rods weighted so as to maintain a vertical position, and of such lengths that they float with their lower ends just clear of the bed. The rate of travel of these rods should be observed along lines in the direction of the flow and equidistant from one another across the channel. The mean of all the observed velocities will give the mean velocity.

But the more ordinary method employed is to observe the maximum surface velocity, and from it to calculate the mean velocity. All the apparatus required is a watch, an empty bottle or other simple float, and means of measuring the cross sections of the channel and intervening length which will be used as the "run" for timing the rate of travel of the float. The mean velocity will then be obtained from the observed maximum surface velocity by the use of the following formula, in which V is the mean velocity, U is the maximum surface velocity, and c is a coefficient having the same values as in formula (3), $V = c \sqrt{R S}$, as given in Tables I. and II. for English and metric measures respectively. These formulas which follow apply only to ordinary canals, drains and water-courses on straight reaches of uniform section.

Formula (6 A). $V = U \times \frac{c}{25{\cdot}3 + c}$ for English measures (c values of Table I.).

Formula (6 B). $V = U \times \frac{c}{14 + c}$ for metric measures (c values of Table II.).

It will be found that, if there are substituted, in the upper and lower

equations respectively, values of c from Tables I. and II. for corresponding values of R—as, for instance, for $R = 3{\cdot}28$ feet, Table I., and $R = 1$ metre, Table II.—the two expressions will give the same numerical result. The Formula (6 C), $V = c_1 U$, can, therefore, be substituted for either, and the values of c be tabulated. This has been done and the following table is the result.

TABLE VI.

VALUES OF c, IN THE FORMULA $V = c_1 U$ FOR FINDING MEAN FROM SURFACE MAXIMUM VELOCITY.

Hydraulic Mean Depth R in feet.	Material of bed and sides of Channel.				Hydraulic Mean Depth R in metres.
	Plastered. Planed Planks.	Dressed Stone. Brickwork.	Rubble Masonry.	Earth.	
1·00	·85	·83	·77	·65	·30
2·00	·85	·83	·79	·71	·60
3·00	·85	·83	·80	·73	·90
3·28	·85	·83	·80	·74	1·00
4·00	·85	·83	·81	·75	1·20
5·00	·85	·83	·81	·76	1·50
6·00	·85	·84	·81	·77	1·80
6·50	·85	·84	·81	·77	2·00
8·00	·85	·84	·82	·78	2·50
10·00	·85	·84	·82	·78	3·00
12·00	·85	·84	·82	·79	3·50
18·00	·85	·84	·82	·79	5·50
20·00	·85	·84	·82	·80	6·00
70·00	·85	·84	·82	·81	21·00
Inf.	·85	·84	·82	·81	Inf.

Formulas (6 A) and (6 B), and their substitute Formula (6 C), apply to all canals on reaches where the maximum surface velocity keeps steadily to midstream, provided the reach itself is fairly straight and uniform.

Willcocks and Holt in "Elementary Hydraulics," written for the use of engineer students, give the following simple directions as to the ordinary method in which a discharge observation should be made.

"Select a fairly straight reach of about 3 kilometres in length, put in a flag on one bank at about the middle point, taking care that the central velocity is the maximum. Measure 25 metres upstream and 25 metres downstream, and put up two more flags, and three flags exactly opposite these on the other bank. Take three cross sections of the canal at these three places. Take the mean of the two outer sections, and then take the mean of this mean and the middle section. This last mean is the actual cross section of the canal. Now allow some twenty circular discs of wood of about 10 centimetres diameter and 2 centimetres thickness to pass down the centre of the canal, and record the number of seconds they each take to pass the interval between the outer flags. The mean of these twenty

observations divided into 50 metres gives the maximum surface velocity in metres per second. Find A (area) and R (hydraulic mean depth) from the cross section in metres; we have U; and c_1 can be obtained from Table VI. by noting carefully the actual condition of the canal. Then $V = c_1 \times U$ in metres per second, and $Q = A \times V$ in cubic metres per second. Of course discharge by surface velocity observations can only be taken when there is no wind."[1]

If the discharge of a wide river with an irregular bed has to be measured, a more elaborate method must be adopted. A cross section of the river must be made with the aid of a steamer to take soundings and of a theodolite to fix the position of the steamer at the moment of taking the soundings. Ranging rods, fixed on the bank in prolongation of the line of the cross section, will enable the steamer to take up its position for sounding on the right alignment. On account of the uneven section the surface velocities must be observed at numerous points, and the calculation of the discharge be made separately for each portion of the cross section to which the observed velocities belong. The total discharge of the river will then be the sum of the discharges of the subdivisions which have been separately calculated.

The formula for open channels, $V = c\sqrt{R\,S}$, as developed in Kutter's formula, can be applied to pipe discharges by giving a suitable value to n. For iron pipes in good order, and from 1 inch to 4 feet diameter, n may be taken at from ·010 to ·012 according to the condition of the inner surface of the pipe, the lower figures being used if the pipe is in exceptionally good condition, and the higher figures when the condition is not so good, though still good.

There are thus six formulas which are most essential for irrigation engineers, namely:

Formula (1). Discharge $Q = A \times V$ for all cases.

Formula (2). Mean velocity $V = c\sqrt{2\,g\,H}$ for sluice-ways.

Formula (3). Mean velocity $V = c\sqrt{R\,S}$ for open channels and pipes.

Formula (4). Discharge $Q = \frac{2}{3}\,c\,A\sqrt{2\,g\,h}$ for clear-overfall weirs.

Formula (5). Discharge $Q = c \times l\sqrt{2\,g\,d_1}\,(d_2 + \frac{2}{3}\,d_1)$ for submerged weirs.

Formula (6 A). Mean velocity $V = U \times \dfrac{c}{25{\cdot}3 + c}$ for English measures,

or Formula (6 B), mean velocity $V = U \times \dfrac{c}{14 + c}$ for metric measures,

or Formula (6 C), mean velocity $V = c_1\,U$, in place of Formulas (6 A) and (6 B).

APPENDIX III.

BOOKS OF REFERENCE.

In the following list those works of reference only are included which deal with irrigation, or one of its main sub-heads, in a general way. Books, reports, proceedings, and pamphlets, which treat of special irrigation schemes or constructions, are too numerous for accommodation in an appendix. Catalogues of such works exist in technical libraries.

Irrigation, General.

"Irrigation." Transactions of the American Society of Civil Engineers. International Congress. 1904.

A collection of papers on irrigation (1) under British engineers, that is, in India and Egypt; (2) in Java; (3) in the United States; (4) in France; and (5) in the Hawaiian islands, with discussions on the papers.

"Irrigation Engineering," by H. M. Wilson. Publishers: Chapman & Hall, London, and Wiley & Sons, New York. 1903.

The subject is viewed from an American standpoint. Most of the illustrations are borrowed from the United States, but some are drawn from India and other countries. A list of books of reference (chiefly American) is given for each section of the subject.

"Manual on Irrigation Works," by B. O. Reynolds. Printed Government Press, Madras. 1906.

This book is written with India as the author's standpoint, and is a text-book for the use of the students of the Madras Engineering College, compiled by one of the staff.

"Irrigation Manual," by Lieut.-Gen. J. Mullins. Publishers: E. and F. N. Spon, London and New York. 1890.

This is also written from an Indian standpoint. It contains many plates of irrigation works existing in 1890.

"Irrigation Canals and other Irrigation Works," by P. J. Flynn. Published San Francisco, California. 1892.

The subject is treated generally, with illustrations borrowed from America, India and other countries.

"Hydraulic Works," by Lowis D'A. Jackson. Publishers: Thacker & Co., London. 1885.

Statistics are given of the hydraulic works and hydrology of England, Canada, Egypt and India.

Irrigation in Different Countries.

India.

"The Irrigation Works of India," by R. B. Buckley. Publishers: E. and F. N. Spon, London and New York. 1905.

This is the most complete and recent work which treats of irrigation in India as a whole. The magnificent irrigation works are described and freely illustrated; and the lessons taught by experience, gained in irrigation schemes of large scale and extending over long periods, are recorded. Almost all matters connected with practical irrigation are dealt with.

"Irrigated India," by Hon. A. Deakin. Publishers: Thacker & Co., London. 1893.

This book contains a description of the irrigation and agriculture of India and Ceylon as viewed by an Australian.

"Irrigation in India," by H. M. Wilson. Printed Government Printing Office, Washington. 1892.

The subject is presented as viewed by an American engineer.

"Report of the Indian Irrigation Commission," presided over by Sir Colin Scott-Moncrieff. Publishers: Eyre & Spottiswoode. 1903.

This report contains a record of the evidence collected by the Commission concerning the facts about Indian irrigation, and its recommendations as to the policy that the Indian Government should adopt with reference to future irrigation schemes.

Egypt.

Egyptian Irrigation," by William Willcocks. Publishers: E. and F. N. Spon, London and New York. 1899.

This is the standard work on irrigation in Egypt. It contains an account of its canal systems, and records the experience of the irrigation staff gained since 1883 and the opinions formed as a result of that experience.

America.

"Irrigation in the United States," by F. H. Newell. Publishers: Crowell & Co., New York.

This book is intended for the edification of pioneer settlers in a new country, and therefore is not technical. It treats of constructions and methods more or less primitive.

"Irrigation in Western America," by Hon. A. Deakin. Printed Government Press, Melbourne. 1885.

The author gives an Australian's view of the subject.

"Irrigation in Southern California," by W. Ham Hall. Published State Office, Sacramento. 1888.

The irrigable regions and the works and projects of Southern California are described.

Europe.

"Italian Irrigation," by Captain R. Baird Smith, R.E. Publishers: Smith, Elder & Co., London. 1855.

"Irrigation du Midi de l'Espagne," by Maurice Aymard. Publisher: Eugène Lacroix, Paris. 1864.

"Irrigation in Southern Europe," by Lieut. C. C. Scott-Moncrieff, R.E. Publishers: E. and F. N. Spon, London. 1868.

The three foregoing works give general descriptions of the practice of irrigation in the southern countries of Europe. They are not, however, intended to be books of reference for engineers intent upon the more purely technical studies of their profession.

Rivers and Navigation.

"The Improvement of Rivers," by B. F. Thomas and D. A. Watt. Publishers: Chapman & Hall, London; Wiley & Sons, New York.

This book treats of dredging, training works, spurs, bank protection, flood banks, storage reservoirs for navigation, locks, lock gates and valves, fixed dams (weirs), movable dams and regulating apparatus.

"Rivers and Canals," by L. F. Vernon-Harcourt. Published Clarendon Press, Oxford. 1896.

This book deals with the flow, control and improvement of rivers, and the design, construction and development of canals, both for navigation and irrigation, and gives statistics of the traffic on inland waterways.

Dams and Reservoirs.

"Design and Construction of Masonry Dams," by Edward Wegmann. Publishers: Chapman & Hall, London; Wiley & Sons, New York. 1899.

This work gives diagrams and descriptions of the existing high dams studied as a preliminary to the designing of the Quaker Bridge dam and its substitute, the New Croton dam.

"Reservoirs for Irrigation," by James D. Schuyler. Publishers: Chapman & Hall, London; Wiley & Sons, New York. 1901.

Descriptions are given of the various types of dams, and the book is profusely illustrated. Information is also given about the natural and projected reservoirs in the United States of America.

"Masonry Dams from Inception to Completion," by C. F. Courtney. Published 1897.

This small book describes shortly the method of designing and constructing dams.

"Indian Storage Reservoirs with Earthen Dams," by W. L. Strange. Publishers: E. and F. N. Spon, London and New York.

This work treats fully of the design and construction of earthen dams, and of the storage problems connected with them, based on the practice of the engineers of India in the Bombay Presidency.

Drainage and Reclamation.

"The Drainage of Fens and Low Lands," by W. H. Wheeler. Publishers: E. and F. N. Spon, London. 1888.

This book gives a general description of works and machines used in draining low lands.

Construction.

" Design of Irrigation Works," by William Bligh. Publishers: Archibald Constable & Co., London. 1907

This book deals with the theory of design and its practical application to Irrigation Works, with full illustrations; design of existing works are critically examined.

Legal.

" Irrigation Development," by W. Ham Hall. Published State Office, Sacramento. 1886.

A detailed study of irrigation legislation in France, Italy and Spain is made with the view of framing irrigation laws adapted to American conditions.

INDEX.

D.

E.

G.

J.

K.

L.

M.

Y.

Z.

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